

SIRTF Telescope Instrument Changeout and Cryogen Replenishment
(STICCR) Study

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(STICCR) Study

T. C. Nast, D. Frank, C. K. Liu, R. T. Parmley, D. Jaekle,
H. Bulteman, and J. Schmidt
Lockheed Research & Development Division
Palo Alto, CA 94304

T. H. K. Frederking
University of California
Los Angeles, CA

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National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

FOREWORD

This study was conducted for the National Aeronautics and Space Administration through the AMES Research Center, Moffett Field, California, Dr. Walter Brooks, Technical Monitor.

Lockheed Research and Development Division conducted the program within the Cryogenic Technology Group of the Engineering Sciences Directorate. Key individuals who contributed to the success of this program and their contributions are as follows:

- D. Frank – Conducted the cool-down trade studies and was extensively involved in the fluid acquisition and management and cryogen transfer tasks.
- C. K. Liu – Conducted the studies on the mechanical and fountain effect pumps (with T. H. K. Frederking) and the Joule-Thompson devices, and analyzed the overall transfer approaches.
- R. Parmley – Performed the analysis and concept designs for the instrument changeout techniques and was involved in selection of the transfer techniques.
- D. Jaekle – Performed much of the analysis and design of the fluid management devices.
- H. Builteman – Conducted trade studies of operational approaches for service and interface concepts, and developed the timelines.
- T. H. K. Frederking (Consultant, School of Engineering and Applied Science, University of California, Los Angeles) – Consulted in the areas of superfluid-helium transport and the fountain effect and mechanical pumps.
- J. Schmidt – Performed systems engineering to establish interface requirements between the cryogenic engineering and operational functions.

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LIST OF ACRONYMS

Acronym	Definition
ASE	Airborne Support Equipment
AXAF	Advanced X-Ray Astrophysics Facility
BS	Beam Splitter
CCTV	Closed-Circuit Television
CFMF	Cryogenic Fluid Management Facility
CMP	Command and Control Monitor Panel
CRD	Cryogen Replenishment Dewar
CRES	Corrosion Resistant Steel
CRS	Cryogen Replenishment System
CRT	Cathode Ray Tube
CTU	Command and Telemetry Unit
CV	Cryogenic Valve
DC	Direct Current
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
FEP	Fountain Effect Pump
FF	Free Flyer
FGS	Fine Guidance Sensor
FSS	Flight Support System
GSE	Ground Support Equipment
g_0	Acceleration due to gravity at earth's surface
H_2	hydrogen
He	helium
He-II	superfluid helium
ID	Inner Diameter
IRAC	Infrared Array Camera
IRAS	Infrared Astronomical Satellite
IRS	Infrared Spectrometer
IVA	Inter-Vehicular Activity

Acronym	Definition
J-T	Joule-Thompson
L/D	Length to Diameter
LHe	Liquid Helium
LH ₂	Liquid Hydrogen
MIC	Multiple Instrument Chamber
MIP	Multiple Image Spectrometer
MLI	Multilayer Insulation
MMH	Monomethyl Hydrazine
MMS	Multimission Modular Spacecraft
MRMS	Mobile Remote Manipulator System
MSFC	Marshall Space Flight Center
MSS	Modular Support Structure
MTTF	Mean Time To Failure
NBP	Normal Boiling Point
NBS	National Bureau of Standards
NHe	Normal Helium
OMV	Orbital Maneuvering Vehicle
OD	Outer Diameter
ORR	Orbital Regression Rate
ORU	Orbital Replaceable Unit
PC	Precooler
P/L	Payload
POCC	Payload Operations Control Center
PP	Porous Plug
RCS	Reaction Control Subsystem
RM	Reference Mission
RMS	Remote Manipulator System
RPM	Revolutions Per Minute
SFHe	Superfluid Helium
SIRTF	Space Infrared Telescope Facility
SM	Secondary Mirror
ST	Space Telescope

Acronym	Definition
STICCRS	SIRTF Telescope Instrument and Cryogen Changeout Replenishment Study
STS	Space Transportation System
ScHe	Supercritical Helium
UCLA	University of California at Los Angeles
VCS	Vapor-Cooled Shields
VLPS	Vapor-Liquid Phase Separator

EXECUTIVE SUMMARY

Overview

The overall objectives of this study were to examine the system implications of building and operating the 1-m class, cryogenically cooled infrared telescope which can be serviced in orbit. The scope of this study was to develop system concepts of the Space Infrared Telescope Facility (SIRTF) that permit on-orbit servicing. The principal elements of the study addressed replenishment of the cryogen and replacement of the cryogenic instrument assemblies and telescope cryogenic mechanisms. Issues relating to cryogen replenishment were emphasized.

The most significant results of this study were:

- (1) Several approaches were identified which lead to efficient refill of SIRTF in orbit. These employ superfluid helium (He-II) supply with transfer by mechanical pump or fountain effect pump (FEP) and liquid acquisition in the supply by means of a surface tension device (gallery). Inclusion of a cool-down capability of the SIRTF appears necessary but substantially complicates the options and increases the supply tank quantity required. Identification of the optimum transfer technique requires further system analysis and ground test, but orbital testing may not be necessary.
- (2) Four concepts were examined for changing out the scientific instruments; two concepts requiring the SIRTF to be near room temperature and two permitting changeout while cold. These concepts appear feasible but need additional analysis and development to assess cost and risk factors.
- (3) Impacts on the space station of cryogen replenishment and instrument changeout of SIRTF appear to be minimal.

Background

The first SIRTF designs originated as a Space Transportation System (STS)-borne system flown on sortie missions. The limit of the life of that system was the time that the orbiter could stay aloft. Advances in cryogenic technology, the success of IRAS, and results of Lockheed's Long-Life Mission Feasibility Study have indicated that the SIRTF mission could better be accomplished as a free-flyer spacecraft. This would extend the mission life from days to years. The next logical extension of this concept is to extend the useful orbital life to multiples of the intrinsic life by replenishing the cryogen expendables on orbit.

Another important contributor to the useful life of the system is the lifetime of the scientific instruments and spacecraft mechanisms. This lifetime can be extended by a design which allows servicing or replacement on orbit. Thus the 10-day mission as a sortie flight could grow to a possible 15 years as a serviceable free flyer. This would produce a national asset that is significantly more cost effective for data gathering and is capable of integrating newer instrument designs as technology or new findings in science and data analysis warrant.

With extended life of the cryogen system, thermal design becomes more critical. The system issues of reliability and redundancy to eliminate single-point failures become more important. Mean time to failure of all components must be well documented and understood.

Once the system technical and cost trades are made to optimize the use of cryogens and to maximize the hardware life, the next step is to design the system so that the expendables can be replenished and the hardware can be serviced. Servicing may be required because of possible hardware failures, advances in the scientific instrument design, or new instruments or special diagnostics required to explore newly discovered infrared sources or features.

This study is one of two parallel studies funded by NASA-ARC to investigate the issues of on-orbit replenishment of cryogens and replacement of cryogenic components and instruments.

During the contract the scope of work was expanded to include development of a system concept for the airborne servicing equipment and the ground and space hardware to support it, and to investigate the impact on the space shuttle and space station of servicing space systems with this equipment.

Major Conclusions

The major conclusions of this study are in four areas:

- Operations analysis
- Orbital cryogen transfer
- Space station impacts
- Instrument changeout

1. Operations Analysis

The findings of the operations analysis study are:

- Attaining sun-synchronous operational SIRTf orbit is impractical with the single existing shuttle flight
 - Two flights would be required to deliver OMV and SIRTf separately
- 28.45-deg orbit at 600 to 900 km is readily achievable
 - Resupply of low-inclination SIRTf can be accomplished:
 - with the shuttle direct injection
 - with the OMV transported by the shuttle
 - with a space station based OMV
- The SIRTf cryogen resupply imposes no undue constraints on either the shuttle or space station
 - Replenishment by shuttle requires dedicated application of this limited resource for up to 14 days per mission
 - Replenishment by space station based OMV implies high-reliability design needed for SIRTf because of limited accessibility
- Manned setup and termination of cryogen replenishment process are straightforward and preferred over application of conceptual robotic systems
- Impact of manned operations and use of the shuttle on the SIRTf mission are minimal

- Man rating of SIRTf and resupply airborne support equipment adds weight and cost
- Science return is greatly expanded
- Servicing a platform-mounted SIRTf using the OMV is severely time-limited unless it is sun-synchronous or co-orbiting (same altitude) with space station

2. Orbital Cryogen Transfer

Several techniques have been identified which will theoretically allow efficient filling of SIRTf in orbit. Questions remain about optimization of the system with regard to fill efficiencies and operational simplicity. Two techniques involving pumps have been identified for further system analysis - the FEP and a mechanical pump. The transfer losses of the system appear to be relatively small, about 10 percent or less, for refilling a cold tank. For cool-down and top-off of a warm tank, the losses can be quite large, 50 percent or greater. No compelling arguments for elimination of the warm-tank refill capability have been presented. In addition to the possibility of an unexpected cryogen depletion, it may be desirable to warm up the system to change instruments. It appears that the required resupply tank capacity to refill a 4000-L SIRTf tank is about 10,000 L for a warm tank refill.

A technology development plan was performed. The key elements of this plan are:

- Detailed systems analysis on the transfer thermodynamics, fluid flow, and pressure drop
- Development of key components such as the transfer pumps, zero-g liquid drain system (for He-II), venting system for H₂ (foam metal), special instrumentation and valves, and high vent rate porous plugs.
- Development of a ground test facility which includes a supply of receiver tank, transfer lines, necessary pumps, and provisions for venting at the necessary rates. This is considered to be one of the key technology items for the He-II transfer technology.

We do not feel that orbital testing is required to establish the necessary confidence in orbital transfer capabilities. All of the required technology except the low-g liquid-He-II draining can be demonstrated under 1-g conditions. We feel that adequate test and analysis of this low-g draining system can be conducted without orbital test. It is prudent to make a final decision on the necessity for orbital testing after component development and ground test.

3. Space Station Impacts

The hardware impact on the space station are simply the accommodation of the cryogen replenishment system (CRS) and the SIRTf. The baseline concept calls for replenishment ASE [without cryogen replenishment dewar (CRD)] to be carried to the station on a routine resupply and stored there for the duration of the SIRTf mission. The CRD would then be delivered shortly before the replenishment operation and subsequently returned to earth for storage, maintenance, and refilling prior to the next service mission. Thus, the long-term physical impact on the space station is the occupation of space for the CRS.

Other effects appear to be as minimal as space utilization:

- The SIRTf and its ASE cannot contaminate the station or other users
- It has no impact on the station life
- The CRS will require periodic maintenance at the replenishment cycle
- The power and thermal loads are expected to be small compared to other space station users

More detailed considerations are:

- ASE stored on space station
 - Cryogen replenishment system
 - Instrumentation and control subsystem
 - Specialized EVA tools
- Likely effects on space station
 - Contamination - none
- Potential contamination of SIRTf by effluent of life support system or propellant resupply system
 - Lifetime - none
 - Service and maintenance
- Use of OMV will increase required service and maintenance of OMV
- Permanent housing of instrumentation and control ASE would require maintenance and service at the replenishment period (1 to 2 years)
 - Thermal and power
- Replenishment system expected to use minimal power at widely separated intervals 10 to 12 days on 1- to 2-year cycle
 - No specialized thermal loads or constraints are inherent in storage of the equipment or the helium dewar. A bay to provide sunshade is desirable and may be required pending additional study
 - Structures
- SIRTf replenishment will utilize normal standard structures; and mechanisms similar to the MMS FSS and two mobile remote manipulators (MRMS) will be required to handle SIRTf and OMV simultaneously

4. Instrument Changeout

Four concepts were examined for changing out the scientific instruments. Two concepts require the entire SIRTf to be warmed up while two concepts allowed cold changeouts to be performed. One warm changeout concept and one cold changeout concept were recommended for further development.

Delta Comparisons	Comparison of Warm (Concept 2) versus Cold (Concept 4) Instrument Changeout Concepts	
	Concept 2 (warm)	Concept 4 (cold)
Additional Wt. kg (lb)		+ 206 (454)
Additional Length	+ 8 percent	
Lifetime Difference		- 0.5 percent
Development Cost		+ 11 percent
STS Costs	+ 7 percent	

The warm concept (2) weighs less, has a slightly longer lifetime, and the development cost is less. On the other hand, the cold concept (4) is shorter and has lower shuttle launch costs. Concept 4 also involves concerns over cyrocontamination, astronaut safety, and heat inputs during instrument changeout. Nevertheless, both concepts look technically feasible and should be investigated further.

Concept 2 allows cryogen mechanisms (e.g., valves, beam splitter) to either be serviced or changed out. Concept 4 allows changeouts for all mechanisms except the cold valves. For either concept, changeout of the secondary mirror appears to present the most difficult problems.

Section 1 INTRODUCTION

The first SIRTf designs originated as a Space Transportation System (STS)-borne system flown on sortie missions. The limit of the life of that system was the time that the orbiter could stay aloft. Advances in cryogenic technology, the success of the IRAS, and the results of Lockheed's Long-Life Mission Feasibility Study have indicated that the SIRTf mission could better be accomplished as a free-flyer spacecraft. This could extend the mission life from days to years. The next logical extension of this concept is to extend the useful orbital life to multiples of the intrinsic life by replenishing the cryogen expendables on orbit.

Another important contributor to the useful life of the system is the lifetime of the scientific instruments and spacecraft mechanisms. This lifetime can be extended by a design which allows servicing or replacement on orbit. Thus the 10-day mission as a sortie flight could grow to a possible 15 years as a serviceable free flyer. This would produce a national asset that is significantly more cost effective for data gathering and is capable of integrating newer instrument designs as technology or new findings in science data analysis warrant.

The step from a sortie mission to a free flyer increases the system complexity of the SIRTf. The flight support systems provided by the STS must now become a part of the SIRTf. Capability must be provided to store and transmit the data gathered in observation and in monitoring the vehicle health.

Command systems allowing ground control need to be implemented to allow selection of observing instruments and the programming of mission observations. Attitude control systems must be provided to respond to these commands and point the instrument to the desired location.

With extended life of the cryogen system, thermal design becomes more critical. The system issues of reliability and redundancy to eliminate single-point failures become more important. Mean time to failure of all components must be well documented and understood.

Once the system technical and cost trades are made to optimize the use of cryogens and to maximize the hardware life, the next step is to design the system so that the expendables can be replenished and the hardware can be serviced. Servicing may be required because of possible hardware failures, advances in the scientific instrument design, or new instruments or special diagnostics required to explore newly discovered infrared sources or features.

The scope of this study is to develop system concepts of SIRTf which permit on-orbit servicing and meet the SIRTf preliminary requirements itemized in Tables 1-1 through 1-3. The study addresses replenishment of the cryogenic instrument assemblies and telescope cryogenic mechanisms. Replacement of warm

electronic modules on the spacecraft and telescope rely heavily on previous NASA studies and are addressed herein only to the extent necessary to develop the system concepts and perform system tradeoffs.

In order to service the SIRTf free flyer, it must be retrieved from its orbit and placed on the servicing cradle on the orbiter or space station where replenishment and changeout can be accomplished. Additional system considerations are required to design the free flyer for this servicing capability. Top-level items pertaining to a system design to support servicing are given in Table 1-4.

During this study the program was expanded to include development of a system concept for servicing on the space station. The impacts on space station and space shuttle of an orbit transfer of liquid helium were also studied.

Table 1-1 SIRTf PERFORMANCE REQUIREMENTS

- Spectral range: 1.8 to 700 μm
- Natural background-limited performance: 2 to 200 μm (optics $\leq 7\text{ K}$)
- Aperture diameter: $\geq 0.85\text{ m}$ (1-m class)
- Diffraction-limited performance at 2 μm
- Long-term pointing stability: 0.1 arcsec
- Offset pointing accuracy: 0.15 arcsec
- IR field of view: $> 7\text{ arcmin}$
- Raster scan, spatial chopping, and nodding capability

Table 1-2 MISSION REQUIREMENTS

- Sun-synchronous 700-km 99-deg orbit or low-inclination 900-km 28-deg orbit
- Operational Lifetime: $> 2\text{ years}$ between replenishments (plus 50 percent margin)
- Refurbishable and replenishable
- Instrument changeout
- Launch and recovery by shuttle

Table 1-3 SIRTf TELESCOPE CHARACTERISTICS

- Superfluid helium cryogen
- Asymmetrical sun shade
- Shape and CG matched to existing spacecraft designs
- Internal cryogen tank
- Total instrument heat load: 150 MW
- Instrument heat load at 2 K: 50 MW
- Resealable passively cooled aperture cover

Table 1-4 SYSTEM SERVICING PROVISIONS

- A. Retrieval
 - OMV compatible
 - Retractable solar array
 - Retractable antennas
 - Grapples
- B. Servicing
 - Umbilicals
 - Holding fixtures
 - Hand holds
 - Access to components
 - Unique placement of cryo fill fixture
 - Contamination control
 - Design for EVA
- C. Command, Communications, and Control
 - Unique commands for retrieval
 - Unique commands for servicing
 - Additional instrumentation and monitors
 - Ground system, software, and displays
 - Airborne system, software, and displays
- D. Servicing Station or Vehicle
 - Basic Space Telescope/AXAF system
 - Unique cryogen capability
- E. Validation of Replenishment and Instrument Changeout
 - Temperature probes
 - Pressure measurements
 - Flow-rate meters
 - Functional check of instrument
 - Optical alignment checks
 - Recalibration (radiometric)
 - Software to control all of above
- F. Telescope
 - Replaceable scientific instrument
 - Replaceable optical mechanisms
 - Secondary mirror actuator
 - Beam switch
 - Replaceable fine guidance sensor
 - Sealable aperture door

Section 2

SIRTF BASELINE CHARACTERISTICS

The baseline configuration and operating requirements for SIRTF for this study are defined in "SIRTF Free Flyer Phase A System Concept Description," PD-1006, 3 May 1985. Figure 2-1 shows the long-life concept from this document. SIRTF consists of a 0.85-m diameter Cassegrain telescope mounted in a long-life dewar with an integral torroidal cryogen tank. The scientific instruments are contained within the dewar behind the primary mirror in a 1-m diameter by 1-m long multiple instrument chamber (MIC). Multilayer insulation (MLI) surrounds the dewar. Figures 2-2 and 2-3 are more detailed drawings of the free-flyer telescope baseline. Figure 2-2 shows a single cryogen configuration for a high-inclination orbit. Figure 2-3 is a two-cryogen system for a low-inclination orbit. They show the uncooled electronics chamber containing the portions of the scientific instruments which need not operate at cryogenic temperatures, the attach pins for the OMV, and the location of the fine guidance sensors (FGS).

Figure 2-4 shows the complete SIRTF vehicle with the annular spacecraft as it might appear being serviced on the shuttle. The SIRTF orbits to be considered are 600- to 900-nmi orbits at an inclination of 28.45 deg or 98.2 deg. Access to SIRTF for replenishment and servicing is to be by direct injection of the STS orbiter, by OMV based in the orbiter, or from the space station. SIRTF has no integral propulsion for rendezvous with the orbiter or the space station.

The baseline masses of the SIRTF spacecraft are 3240 kg for the telescope and 4010 kg for the spacecraft, with a total system weight of 7250 kg. This baseline SIRTF has a 4000-L cryogenic tank with superfluid helium (He-II) as the coolant. The baseline supply tank has a capacity of 10,000 L. These are from the referenced Phase A system description. The baseline SIRTF has a complement of six scientific instruments. Since the study was started, a payload of only three instruments has been specified. Changeout schemes are presented which will accommodate both configurations.

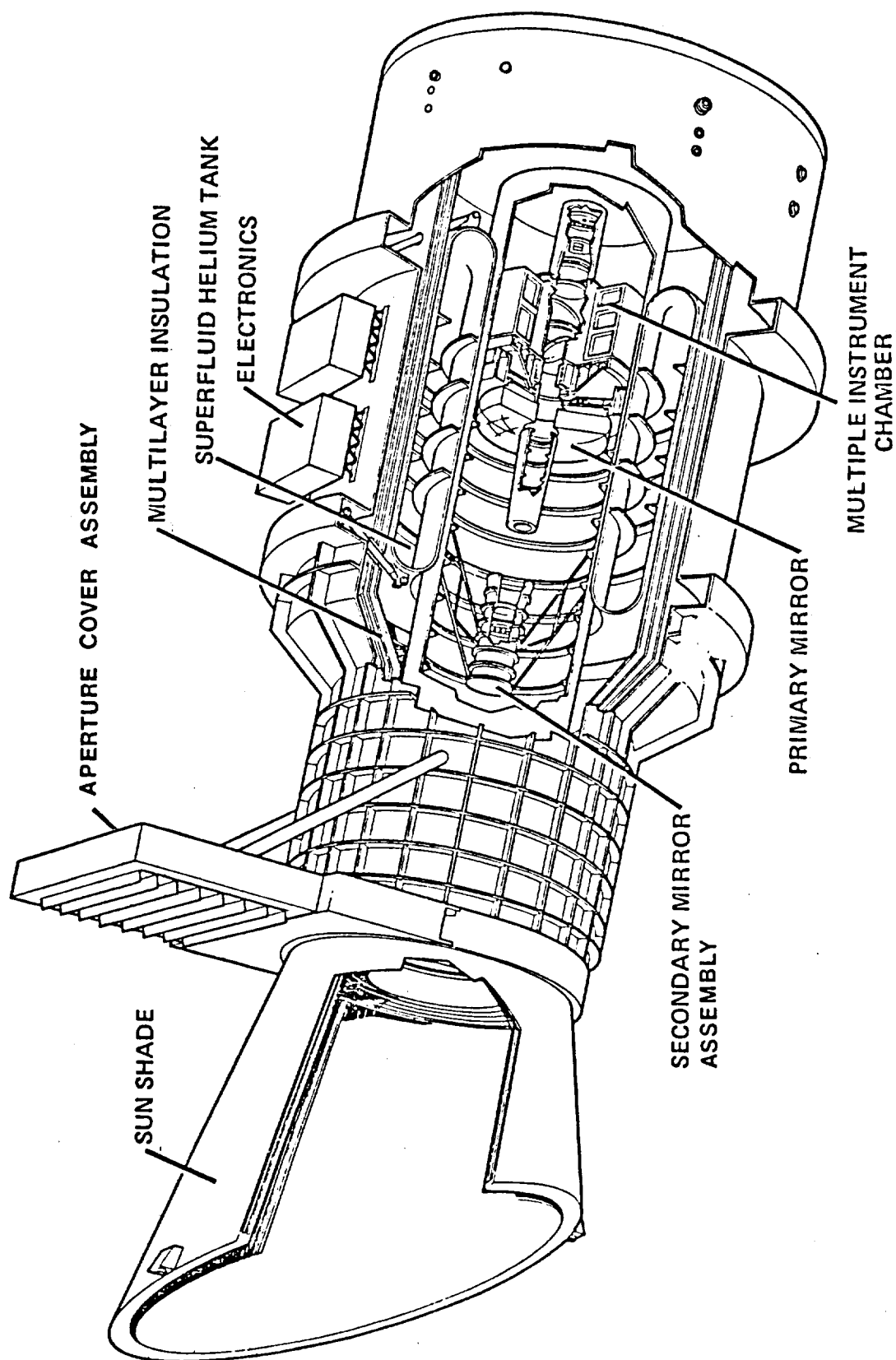
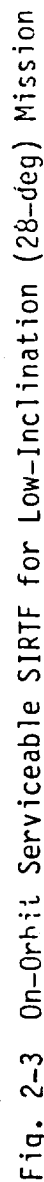


Fig. 2-1 SIRTf Telescope Long-Life Concept

Fig. 2-2 On-Orbit Serviceable SIRTf for Polar Mission (99-deg Inclination)



2-4



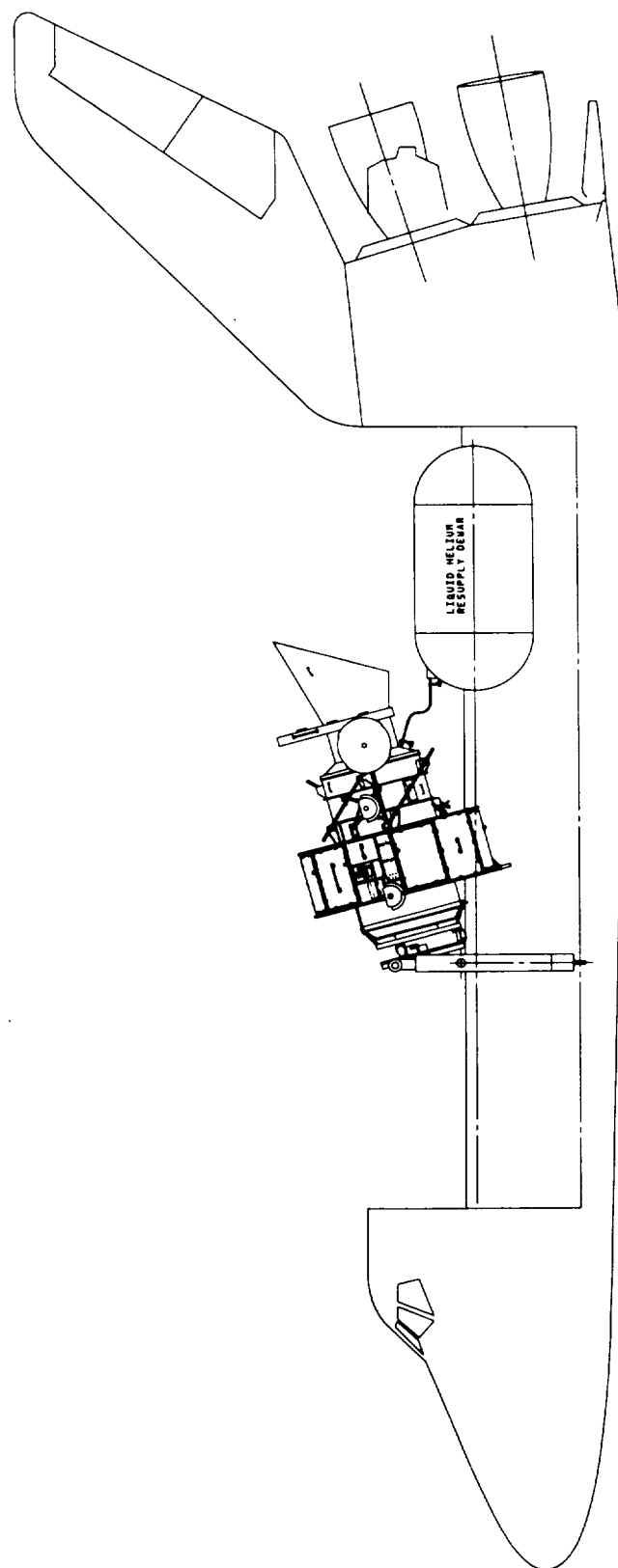


Fig. 2-4 Orbital He Replenishment of SIRT

Section 3 CRYOGEN REFILL ANALYSIS

3.1 OVERVIEW

Figure 3-1 presents an overview of the trade and analysis studies for the cryogen replenishment. Top-level trades were discussed and compared early in the study. The top-level trades were directed at the areas involving substantial departures from the baseline configuration specified in the "SIRTF Free Flyer Phase A System Concept Description," NASA PD1006. These areas primarily dealt with radical tank design such as external tanks to improve the feasibility of a tank swap approach, or cylindrical tanks instead of toroidal tanks. Other major trades dealt with different replenishment techniques for the 28-deg and 98-deg inclination orbits in which an attractive option for the 28-deg orbit is to use a dual-stage approach with superfluid helium (He-II) for instrument cooling and solid hydrogen for absorption of aperture heat inputs and He-II guarding. Other trades dealt with approaches that use separate He-II tanks for separate instruments.

In tank design it became obvious to us early in the study that the present toroidal tank approach is optimum for instrument cooling, and that the thermal losses associated with external tanks, which could be swapped, would greatly affect system lifetime and lead to extremely difficult interface problems, among which was the requirement to make thermal connections between cryogen tank and instrument at a cold condition. Section 4 discusses use of separate cryogen tanks for separate instruments, including the cost and lifetime impacts of such an approach.

For 28-deg versus 98-deg orbital inclinations, it appeared to be expedient in the replenishment studies to consider both liquid-hydrogen (LH₂) and helium (He) transfer, but not to perform completely different and parallel studies on each orbit. This study emphasized He transfer because transfer of LH₂ has been extensively studied, and it is a relatively well behaved well known fluid in low-g environments. It displays surface tension effects similar to storable propellants which have been transferred in space. A program for orbital demonstration is underway, with a demonstration scheduled for 1989. One area relating to solid hydrogen use which was studied was venting during solidification. In this study, the foamed aluminum required for internal heat transfer is considered for a zero-g venting and liquid retention system. The various techniques and approaches for cryogen transfer identified in the proposal were reviewed for completeness, and no new approaches were identified for inclusion in the contract.

3.2 DEWAR/TELESCOPE COOL-DOWN

An on-orbit cool-down may become necessary if warm changeout of cryogenic instruments is required or if uncertainties in lifetime lead to premature depletion of cryogens. Restrictions in on-orbit cryogen top-off opportunities

due to orbital logistics may also lead to depletion of the cryogen. The objective of the tank/telescope cool-down study is to determine the timelines, required amounts of cryogen, and transfer rates to perform the cool-down on orbit.

3.2.1 Thermal Modeling of SIRTf

It is important to have a realistic and detailed thermal model of SIRTf to allow transient cool-down calculations to be made as a function of cryogen, transfer rate, and other parameters.

A SIRTf thermal model used in previous studies was updated to reflect the telescope/dewar configuration described in the NASA document No. PD-1006, dated May 3, 1984, entitled "SIRTf Free Flyer Phase A System Concept Description." Table 3-1 reflects the masses and materials that are used. The model contains 77 nodes connected in a network containing 166 thermal resistors. Both steady-state and transient analyses can be performed with the model using temperature-dependent material properties. The architecture of the model was selected to allow evaluation of:

- Radial and axial temperature gradients within the MIC optical bench and fine-guidance sensing housing
- Temperature gradients within the secondary mirror housing and spider assembly
- Temperature gradients between the dewar and instrument, which include joint thermal resistances generated by either epoxy bond joints or shrink-fit contact thermal conductances
- Selective routing of vapor cooling
- Configuration is for all-He dewar
- Weights are primarily based on NASA Document No. PD-1006, May 3, 1984
- All components assumed to be aluminum except as noted

Table 3-1 WEIGHT SUMMARY

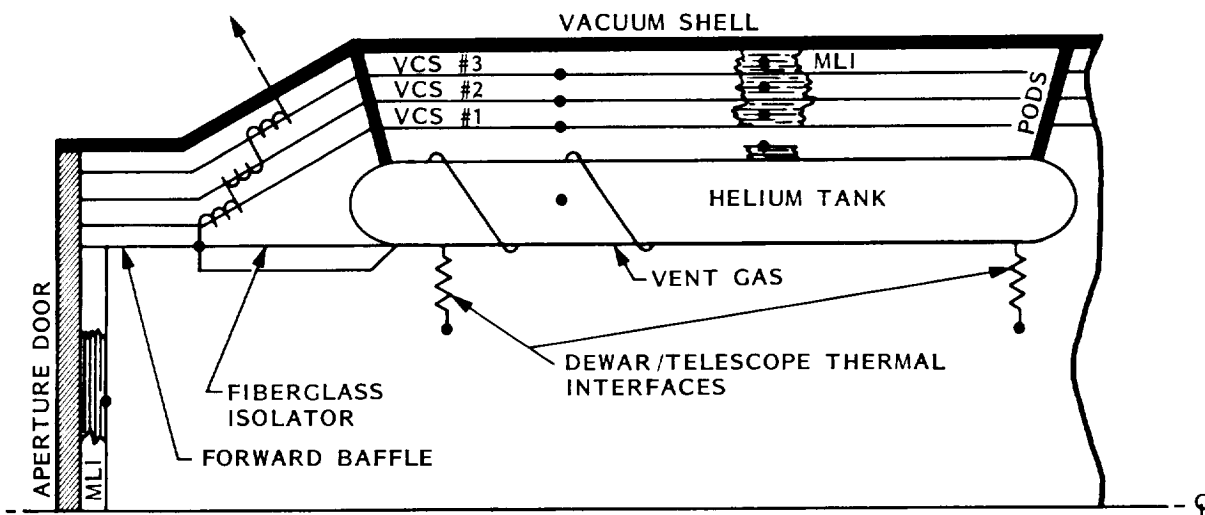
SIRTf Components	Mass (kg)
Helium Tank (4,000 L)	300
Telescope	447
FGS Housing	25
Instrument/MIC	180
Interface Rings	32
Primary Mirror*	80
Secondary Mirror	38
Baffles	92
Thermal Protection System	421
Vapor-Cooled Shields (3)	283
MLI, Aluminized Mylar-Silk Net	138
Total	<u>1,198</u>

*Initial trade studies assumed aluminum primary mirror; additional runs described in Section 3.2.4 studied effect of quartz.

Figure 3-2 shows the overall model network used for the cool-down studies, while Fig. 3-3 presents details for some of the major telescope elements. The model includes assessment of temperature gradients within the individual elements such as primary mirror, secondary mirror assembly, and optical bench.

The thermal attachment between the cryogen tank and the telescope assembly is a dominant driver for the cool-down cryogen requirement. The thermal resistance of this connection was varied parametrically in the study, but what we think is a reasonably straightforward set of flexible braids was assumed for a baseline starting point. We assumed that flexible copper braids were used; one set located between the He tank and the secondary attachment point, and a second set between the tank and interface ring near the primary mirror. The assumed construction and number of braids are indicated in the figure. A number of braids which led to a thermal resistance of 0.4 K/W at each location was selected initially.

Another key assumption for this analysis is that the vent line through which the He boil-off gas leaves the tank is thermally attached to the tank for a sufficient length to produce a 100-percent efficient heat exchanger between the gas and the tank. It is necessary to ensure that all of the helium flowing into the tank is vaporized and warmed to the tank temperature for efficient cool-down and use of the maximum enthalpy of the vented gas. Estimates of the line length to achieve high efficiencies have been made. Some of the primary results are presented in Fig. 3-4 for a simple on-wall tubular heat exchanger and the tank at 300 K. This shows that a 1-cm-diameter



- He VENT GAS IS ROUTED TO FORWARD BAFFLE AND VAPOR-COOLED SHIELDS WITH 100% EFFICIENCY HEAT EXCHANGERS
- APERTURE DOOR CLOSED WITH 1.27-cm INSULATION BLANKET ON INTERIOR
- TWO DEWAR/TELESCOPE THERMAL INTERFACES, EACH 0.4 K/W AT 300 K
- 12 PODS THERMALLY GROUNDED TO VAPOR-COOLED SHIELDS
- RADIATION RESISTORS BETWEEN APERTURE DOOR, DEWAR, AND TELESCOPE ASSEMBLIES

Fig. 3-2 He Dewar Temperature Model Geometry

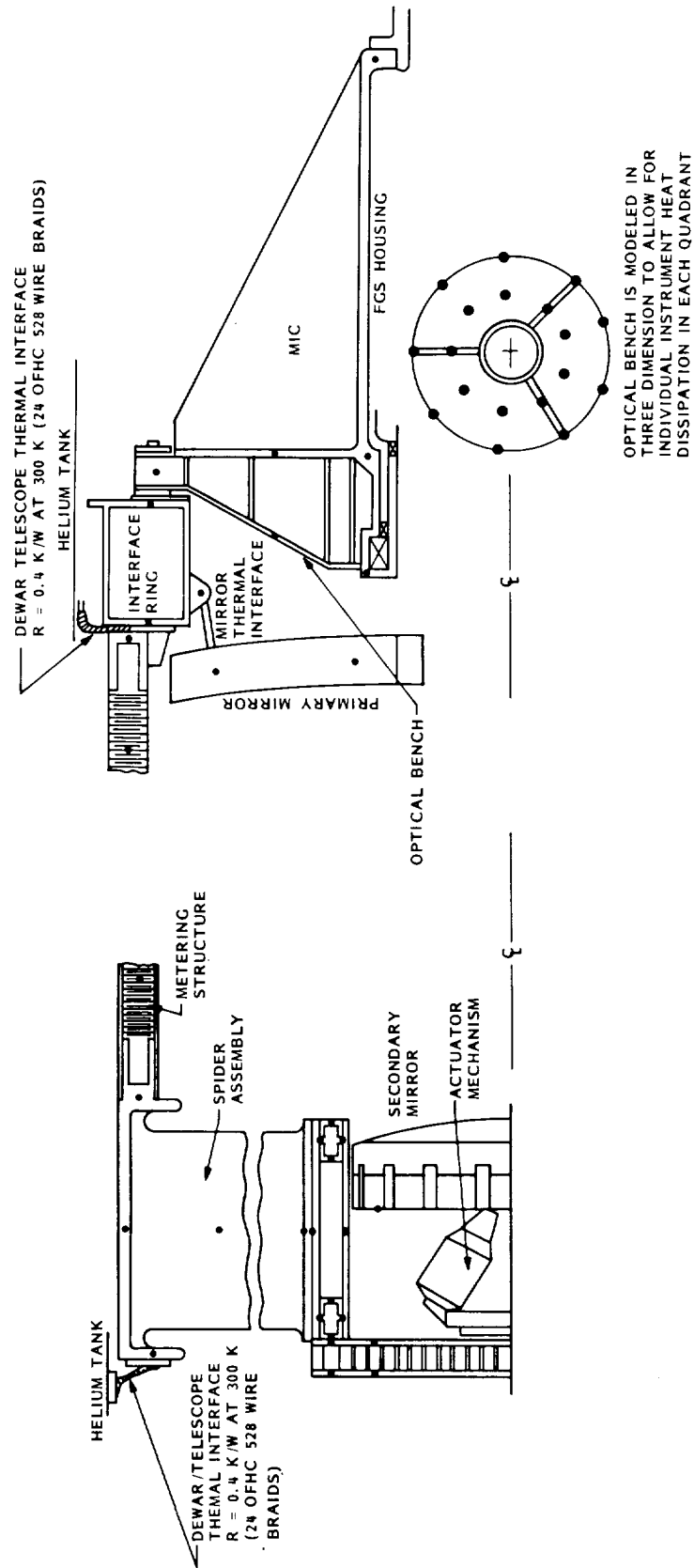


Fig. 3-3 Telescope Temperature Model Geometry

or complications. Choosing the optimum technique to achieve this requires further study. We have assumed a 100 percent efficiency in our studies, a value we feel can be easily approached without difficulty. We have also assumed that during the cool-down the aperture door with 1.27 cm of insulation on the inside is closed to reduce heat inputs from that source.

3.2.2 Typical Telescope Cool-Down

For the all-He system, a baseline cool-down was examined initially to determine the major parameters determining the timelines and quantities of He. The four most significant are:

1. Initial telescope temperature
2. Cryogen transfer rate
3. Vapor routing during cool-down
4. Thermal resistance between dewar and telescope

This section describes a baseline cool-down, and the following section illustrates some variations of the above parameters. The dewar/telescope thermal connection is at two locations - the secondary mirror spider support and the optical bench interface ring. These link locations were chosen in the original model to aid in maintaining the secondary mirror assembly at a minimum temperature, since the secondary actuation system may generate substantial heat. The necessity for the locations, or the desirability of more than the thermal links requires additional study and a more definitive value of the actuator heat generation. For these studies, the cryogen transfer rate is assumed to be constant, and the transfer losses are neglected.

For this baseline cool-down, a transfer rate of 100 L/h of liquid helium (LHe) and a thermal resistance of 0.4 K/W at each of the two dewar/telescope locations is used. The dewar and telescope initial temperature is 300 K, reflecting a system which had been depleted of cryogen and allowed to completely warm up to ambient conditions.

Figure 3-5 shows the transient cool-down. The helium tank is cooled first, with all the other masses after it. The energy removed from the telescope masses is conductively transferred to the helium tank and removed primarily by the helium vaporized in the warm tank. The total helium cooling capacity at the tank due to the vaporization and 100 percent efficient on-wall vapor heat exchanger is (Fig. 3-6)

$$Q = \dot{m}[H_v + C_p(T_w - T_{SAT})]$$

where

- \dot{m} = mass flow rate (g/s)
 H_v = heat of vaporization (J/g)
 C_p = vapor specific heat (J/g-k)

- DEWAR/TELESCOPE THERMAL INTERFACE OF 0.4 K/W AT EACH OF TWO LOCATIONS
- $T_{VAC} = 300$ K
- SIRTf HELIUM LOADING RATE 100 L/h

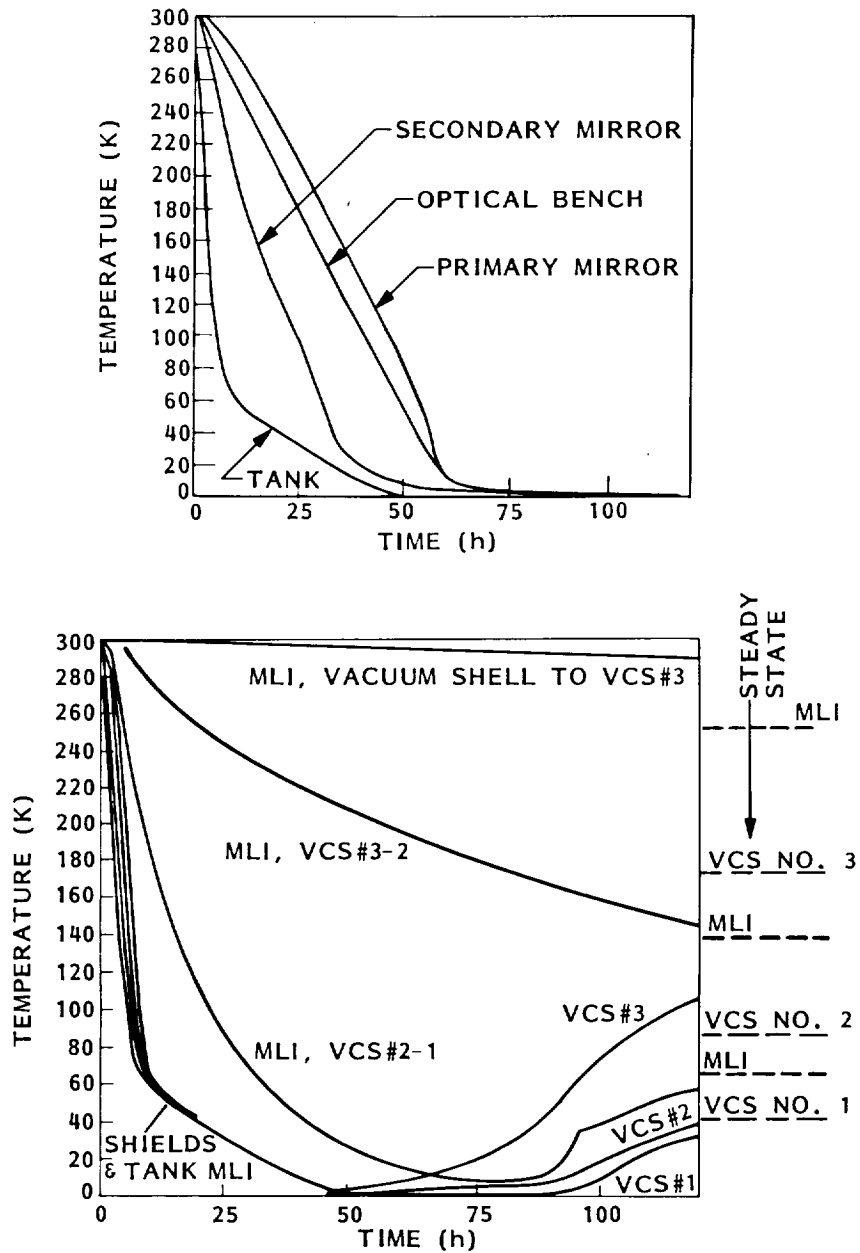


Fig. 3-5 SIRTf Transient Cool-Down

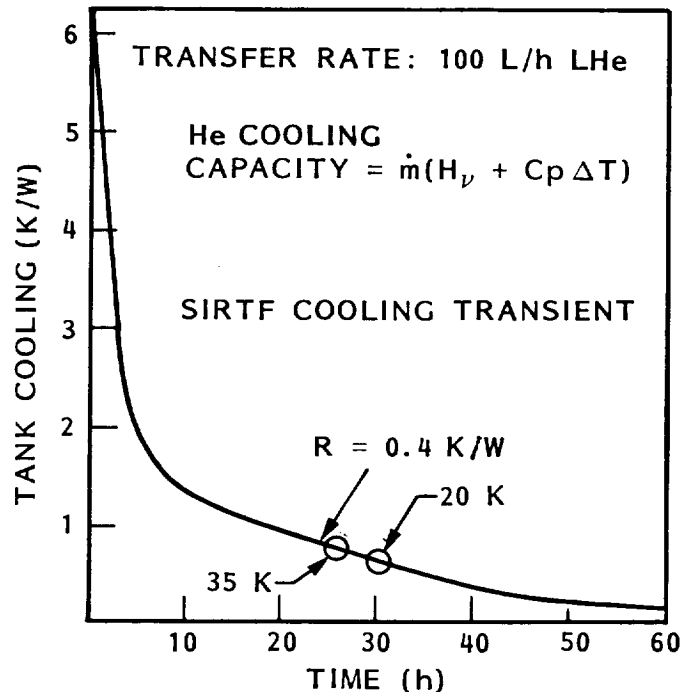


Fig. 3-6 He Cooling at Tank

T_w = tank temperature (K)
 T_{SAT} = saturation temperature of incoming liquid (K)

This amounts to thousands of watts during the first 24 h and shows the importance of this on-wall heat exchanger. During this period practically all cooling is in the heat exchanger, since the heat of vaporization of LHe is small. The cool-down rate would be the same if normal LHe or cold He vapor were used.

During the cool-down, while the tank is above the saturation temperature of the liquid, all the transferred cryogen will be vaporized and vented from the dewar. The vapor passes through the forward baffles and shields, and because of the high venting rates causes them to be subcooled below their steady-state operational temperature. This is shown in Fig. 3-5, where after 20 h they are all cooled to below 40 K. The temperature of the insulation is also shown in this figure. After 120 h the warmer blankets have not been cooled to their steady-state temperature.

The reason for the long
thickness of 7.6 cm ba
Phase A System Concept
times for 2.5-cm thick
at this laboratory ar
is proportional to th

date
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iter MLI blanket is its assumed
contained in "SIRTF Free Flyer
3 May 1985. Typical cool-down
lly and analytically confirmed
ays. Since the relaxation time
red ($\theta \sim L^2/\alpha$, where L is

blanket thickness and α is thermal diffusivity), the 7.6-cm blanket assumed would have a relaxation time as great as 9 weeks. The heat stored in the blanket is removed eventually by vapor cooling, and this does not appear to represent a significant effect on lifetime. However, additional analyses of the soak time and the optimum blanket thickness are required.

Liquid will begin to accumulate in the tank once it is cooled to the saturation temperature. However, high venting rates will persist until the heat load to the cryogen tank drops off. Figure 3-7 shows the venting rate profile, where at 52 h into the cool-down accumulation of liquid in the tank begins, and therefore the venting rate begins to drop. The amount of cryogen accumulating in the tank is shown in Fig. 3-8. After 98.5 h the tank is full. The heat load to the tank at this time is fairly low (2.05 times the steady-state rate), and therefore there is no need for a final subsequent top-off of LHe. The total amount of He to cool SIRTf from 300 K and fill the 4,000-L tank at a transfer rate of 100 L/h is therefore 9850 L.

This example case provides data on the plumbing requirements of SIRTf to allow orbital cool-down and refill. The pressure drop in the system must be compatible with the required flow rates over a range of temperatures. The operational porous plug cannot pass the required quantity of gas flow during cool-down. A line which bypasses the porous plug with suitable control valves must be provided for the cool-down. The requirements for the line size are dependent upon the available pressure for transfer. The mechanical and fountain-effect pumps can provide pressures near or in excess of atmosphere, but the attendant system penalties require assessment.

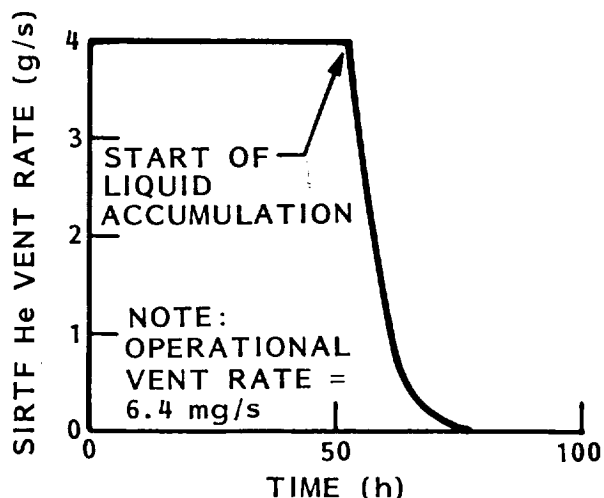


Fig. 3-7 SIRTf He Venting Rate During Cool-Down ($\dot{V} = 100$ L/h)

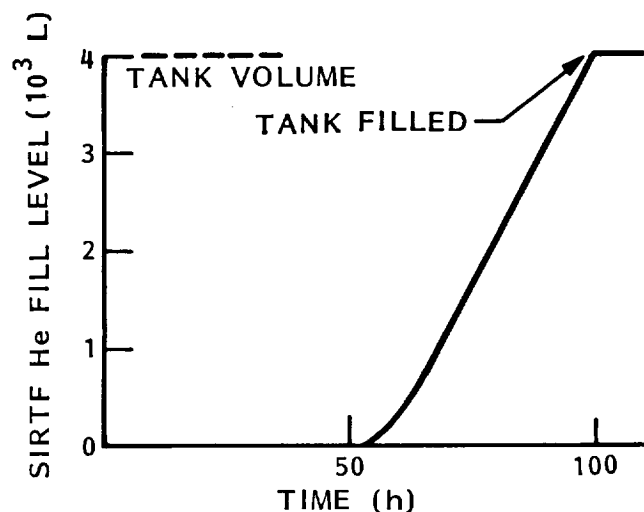


Fig. 3-8 SIRTf He Fill Level During Cool-Down and Replenishment ($\dot{V} = 100$ L/h)

Figure 3-9 summarizes the requirements for line size and pressure for various flow rates. These predictions were obtained with a flow model program which assumes exit line choking and can incorporate various line sections at various temperatures. In the calculations it was assumed that the exit temperature remained at 300 K, that the inlet was the same as the tank temperature, and the line temperature gradient was linear between these values. For a 2-cm-diameter line, the pressure requirement is 220 torr at the beginning of flow when the tank is warm and drops to 60 torr when the tank begins collecting liquid. The required pressure variation can be supplied by a variable speed mechanical pump or variable heat input to a fountain effect pump. The required pressure can also be supplied by using a supply tank with normal He and letting the supply tank pressure collapse as fluid is withdrawn from the tank.

Another transfer technique is to maintain constant pressure in the system and allow the flow rates to vary. Figure 3-9 shows that if a constant tank pressure of 200 torr were monitored, the initial flow would be 90 L/h at 300 K, 140 L/h at 150 K, and 35 L/h at 2 K due to the varying pressure drop with temperature. This approach may be superior to the constant flow rate approach, but we have not combined the flow rate model and the tank cool-down model to perform this analysis.

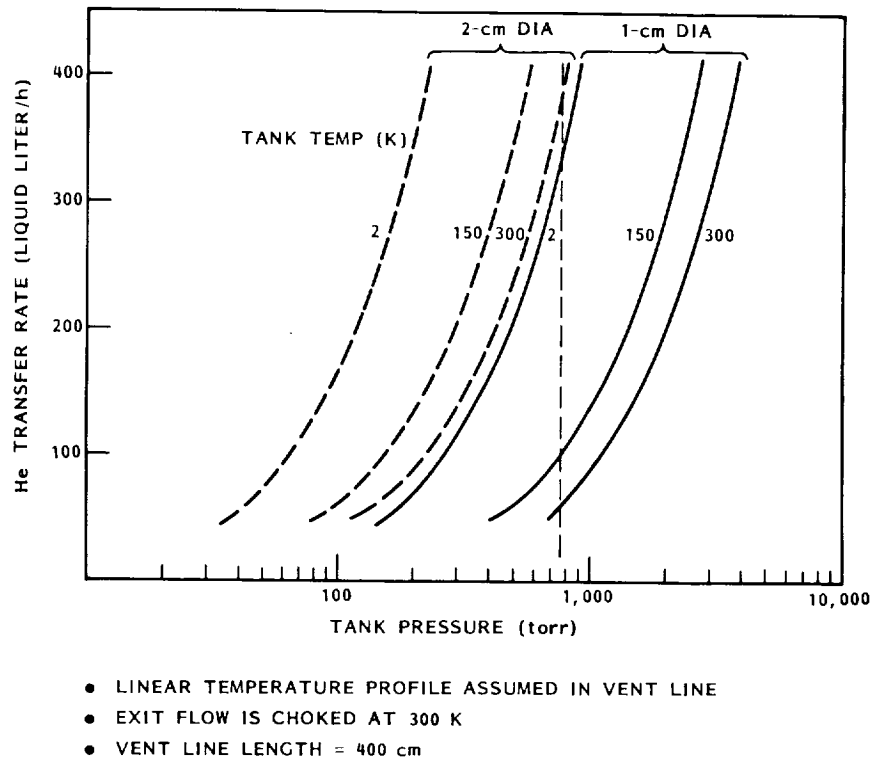


Fig. 3-9 Transfer Rate Dependence on Pressure and Temperature

An additional consideration is the high vent rates which occur between the start of liquid collection and the collection of fill (Fig. 3-7). During this time liquid loss must be prevented, and it is desirable to use the proven concept of the porous plug to effect phase separation. The operational porous plug is designed for the low flow rate and will not operate satisfactorily during this period. It is therefore necessary either to develop a porous plug with much greater flow capacity which can separate liquid and vapor over a large flow range or develop some alternative approach. Some approaches for high flow rate porous plugs are discussed in Section 3.3.3. The following section describes some variations from the baseline and their implications.

3.2.3 Cool-Down Trades

This section presents variations of some of the parameters that effect the cool-down timeline and cryogen quantities. The principal parameters are the transfer rate, dewar/telescope thermal resistance, and initial tank temperature.

The transfer rate was varied from 50 L/h to 400 L/h, and, as in the previous example, the flow rate was kept constant during the cool-down and fill. The thermal interface was kept at 0.4 K/W at each of the two locations. As expected, the larger the transfer rate the faster the cool-down and fill will take place. However, the quantities of He required will differ. For transfer rates of 400 L/h or higher, the telescope and dewar are cooled and filled

before the heat rates to the tank are appreciably reduced. After the tank is filled, a large portion is boiled off and a subsequent top-off of the tank is required. At these higher flow rates, high venting rates persist for longer periods while the tank has accumulated liquid. Figures 3-10 and 3-11 show these results for initial temperature of 300 K.

To decrease the high venting rates while liquid has accumulated in the tank, it is desirable to cool the telescope and dewar as nearly isothermally as possible. This goal can be approached by decreasing thermal resistances as much as possible. One area which has a major effect is the dewar/telescope thermal interface. Lowering this resistance not only affects the venting rate, but also affects the amount of He required to cool down and fill. This strong dependance is illustrated in Fig. 3-12. The curve showing the "minimum attainable" is the requirement if the dewar and telescope were completely isothermal and contained no temperature gradients. The tank is assumed to be isothermal in all of the studies, however gradients in the telescope structure, i.e., mirrors and optical benches, result for all cases due to the finite thermal conductivity. The difference between the $R = 0$ K/W case and minimum attainable is due to temperature gradients in the telescope. If these could be eliminated by a multitude of copper braids, for example, we could attain the maximum values.

This value is calculated by using the minimum specific cryogen requirement (σ_{\min}) (dimensionless) in Fig. 3-13 which is the ratio of the mass of

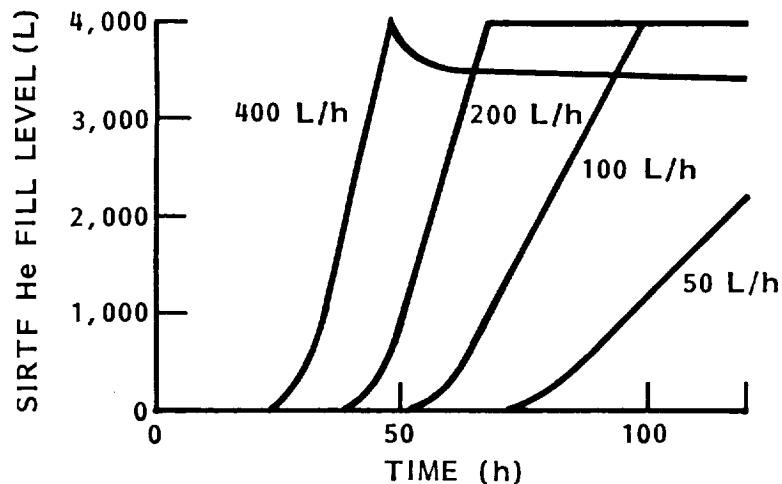


Fig. 3-10 Effect of Transfer Rate on the Cool-Down

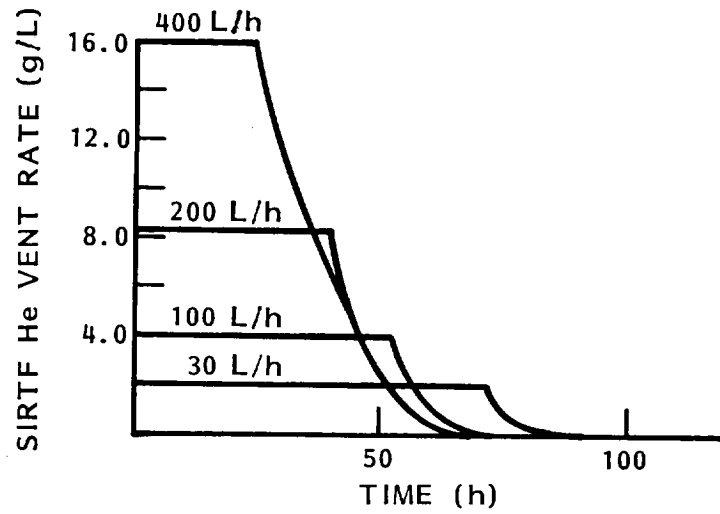


Fig. 3-11 Effect of Transfer Rate on the Vent Rate

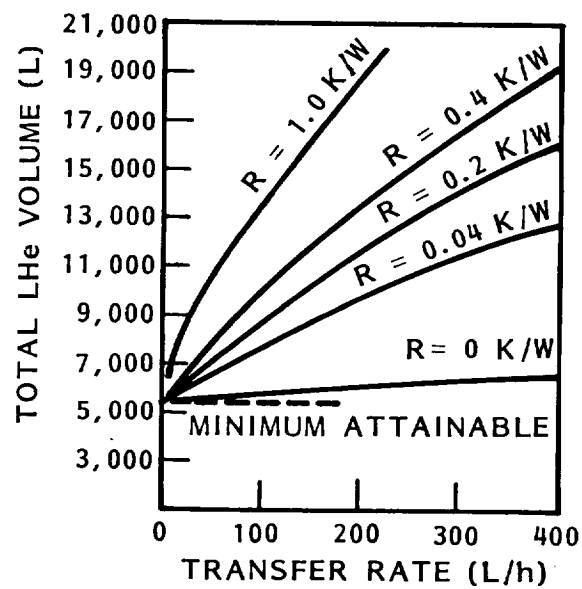


Fig. 3-12 Effect of Dewar/Telescope Thermal Interface

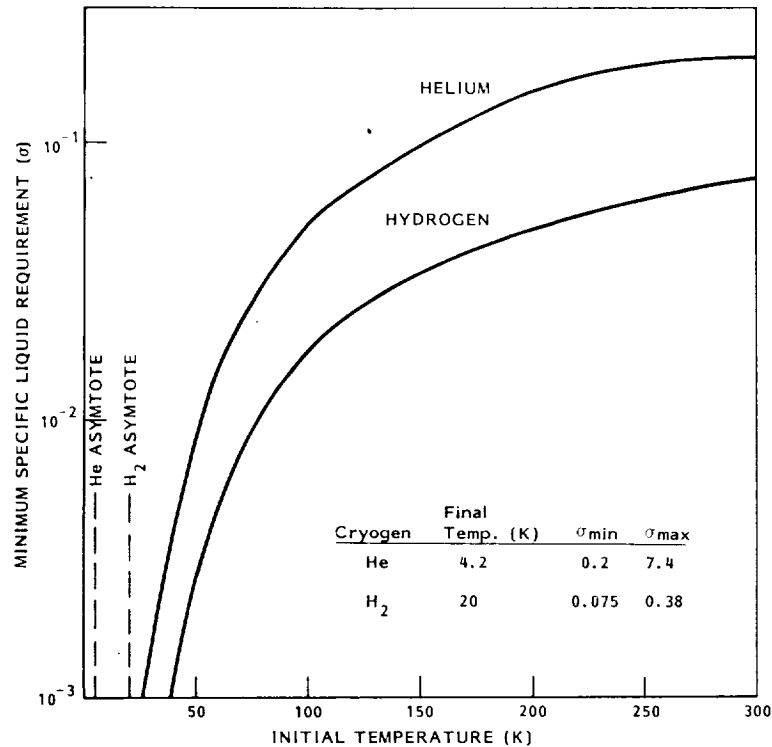


Fig. 3-13 Specific Cryogen Requirement for Cool-Down of Aluminum

cryogen needed to the mass of equipment (aluminum) that is cooled from an initial temperature. The maximum is based on the latent heat of vaporization, while the minimum also uses the sensible heat of the vapor by warming the gas to the temperature of the mass being cooled.

Figure 3-14 summarizes the results of these trades, which show the relationship between the time needed to cool and fill SIRTf and the total amount of LHe required as a function of the transfer rate and dewar/ telescope thermal interface. The enormous benefits of a reduced thermal resistance between the telescope and He tank are evident. For the value of 0.4 K/W taken as the baseline, 10,000 L and 4 days are needed for cool-down and fill, while 6000 L and 1 day are required if the thermal resistance becomes negligible. Clearly this needs substantial investigation in both the design and development of a low-thermal-resistance link.

3.2.4 Effect of Primary Mirror Material

In the transient cool-down trade studies, the primary mirror was assumed to be aluminum. It was desirable to determine if a quartz primary mirror would have significant effects on the cryogen requirements. The primary concern is that, due to the high thermal resistance of quartz, the mirror might not be cooled by the time the cryogen tank is filled. If this is the case, the subsequent soak-down of the mirror would boil off He and effect the lifetime of the dewar. The enthalpy of quartz is lower than aluminum.

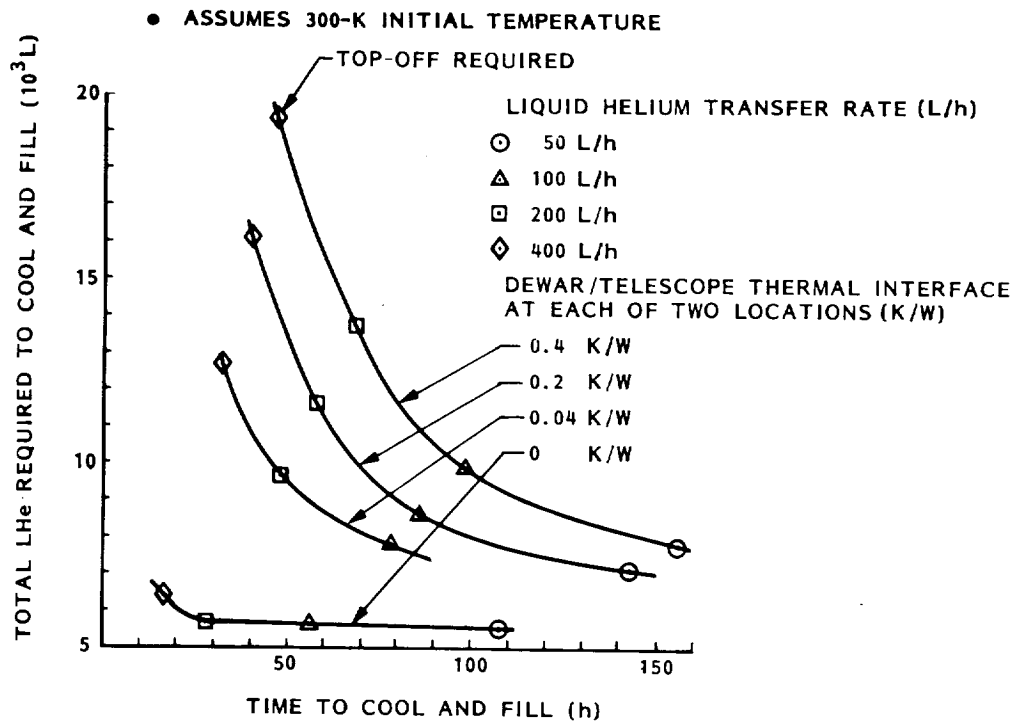


Fig. 3-14 SIRTF Cool-Down Timeline/Cryogen Quantities

The baseline case described in Section 3.2.2 was rerun with the updated quartz mirror. The conductive thermal path for removing heat from the mirror was located around its outer circumference. This causes high thermal gradients in the mirror which will make the mirror cool-down lag behind the rest of the telescope. In actuality this may be undesirable due to the thermal stresses that can develop.

The transient cool-down for 100 L/h and dewar/telescope interfaces of 0.4 K/W is shown in Fig. 3-15. These results show that the mirror is cooled down to an average temperature of approximately 100 K at the time liquid begins to accumulate in the tank. This is not much different from the analyses with the aluminum mirror which was at 70 K at the time liquid begin to collect in the tank. The heat removed from the mirror to cool it from 100 K to its final temperature is removed by vaporizing LHe. Based on the difference in enthalpy of the 80-kg mirror for quartz at 100 K and aluminum at 70 K, an extra 97 L of He are required for cool-down of the quartz mirror. The transient thermal results show that by the time the SIRTF He tank is full, the mirror has achieved its operational temperature. No subsequent top-off is required due to the slower cool-down of the mirror.

3.2.5 Techniques to Reduce Cryogen Quantities

Various techniques of reducing the amount of cryogen needed to cool the SIRTF are available. The most significant is to lower the initial temperature of the system prior to introducing the He. This can be done by passively cooling

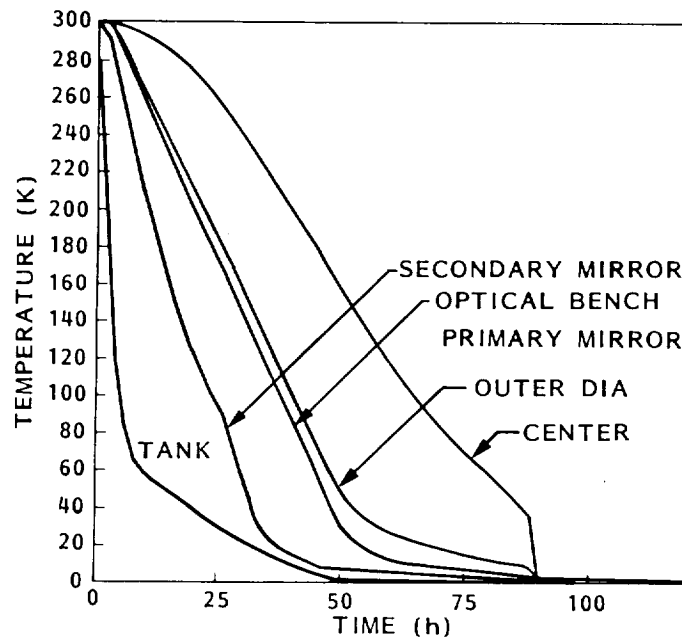


Fig. 3-15 SIRTf Transient Cool-Down with Quartz Primary Mirror

by radiating the aperture to space. If radiative cooling is used, any transient warm-up during capture/docking/door closure must be considered. Use of a mechanical refrigerator was briefly considered. From Fig. 3-6, approximately 500 W of cooling at 20 K is required. The approximate power input to a mechanical refrigerator for this cooling load is 50,000 W for the stirling cycle unit. This requirement is excessive if similar cool-down times are desired. Even for cooling ten times slower, the power requirement is about 8000 W. This approach does not appear feasible. The total He quantities required to cool down and fill based on initial temperature are shown in Fig. 3-16 for constant He transfer rate of 100 L/h.

Dewar/telescope interface design should consider the cool-down requirements, since the interface is an important factor in minimizing the amount of He needed. The interface should have a large area of high-conductivity material. If the interface must be detachable, it can be a shrink-fit connection. Where high thermal conductivity is needed, copper or pure aluminum can be used. If the interface need not carry loads, or if it must be flexible, copper braids can be used. Thermal resistance of copper braid is shown in Fig. 3-17 for a temperature of 300 K. During the cool-down of SIRTf, large dewar/telescope thermal lags occur above 150 K. Figure 3-18 shows the effect of temperature on thermal resistance of different types of copper.

Another option is to use multiple cryogenics. This introduces complexity in the cool-down process and in design of the cryogen supply facility involving

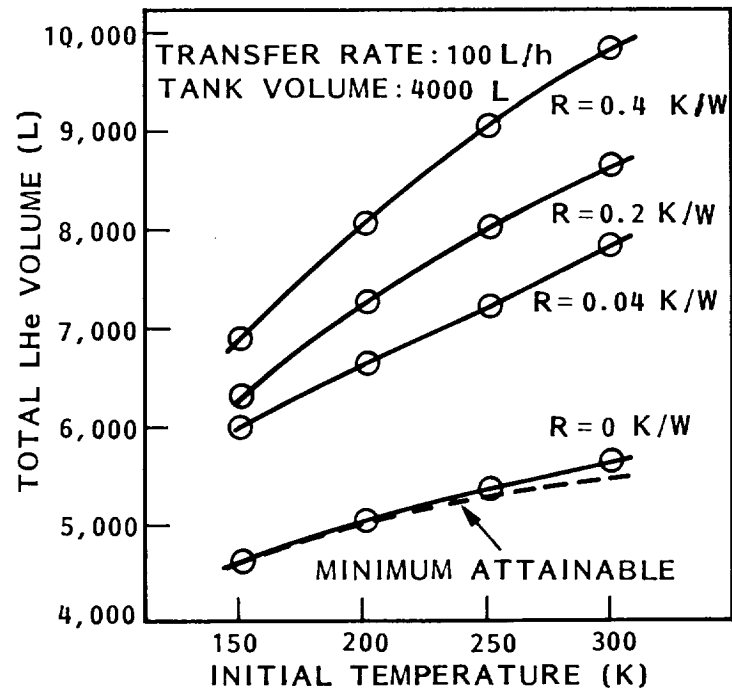


Fig. 3-16 Effect of Initial Temperature on He Quantities

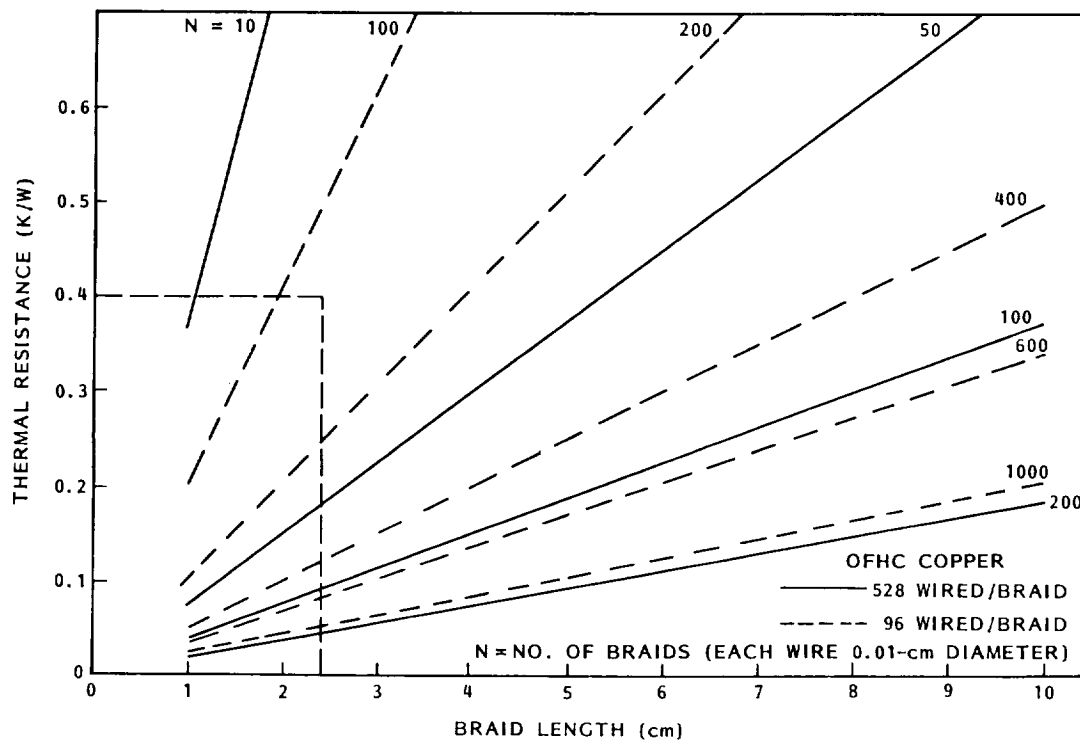


Fig. 3-17 Thermal Resistance of Copper Braids at 300 K

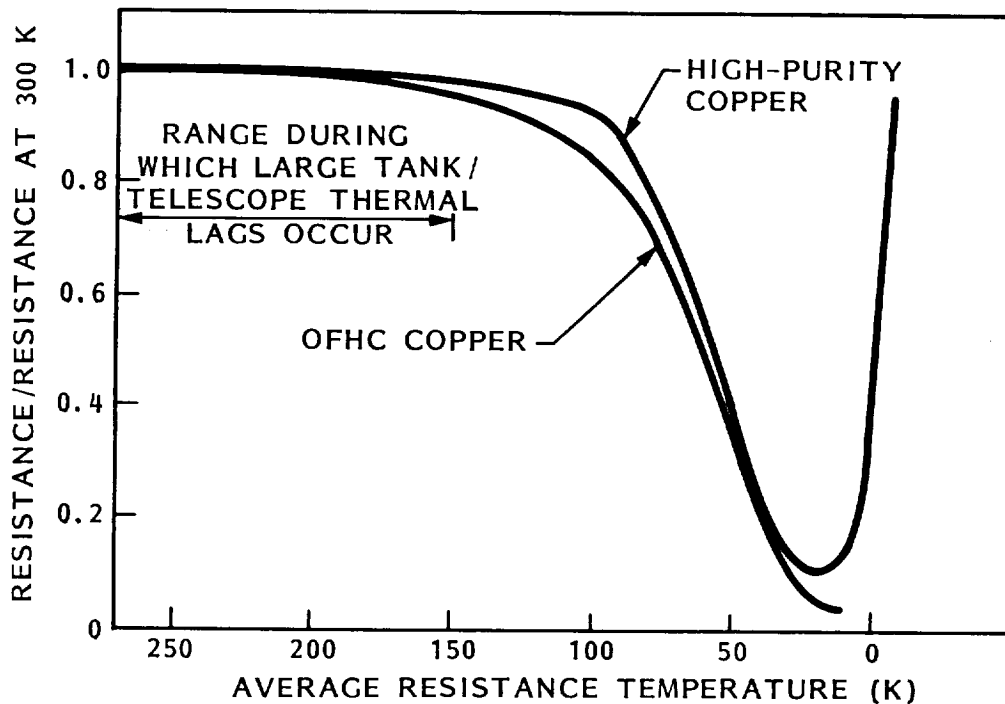


Fig. 3-18 Effect of Temperature on Thermal Resistance

additional tanks, valves, and transfer lines. Two cryogen transfer may be required for the 28-deg inclination orbit version, if it is advantageous to use a hybrid system with He-II and solid H₂.

In this case the dewar/telescope can be cooled with separate cryogenes. Based on the specific cryogen requirements (σ), Table 3-2 demonstrates the advantages of two-stage cool-down with separate cryogenes. The mass and volume ratios are the ratio of total cryogen mass needed to cool aluminum from 300 K to 4.2 K by initially using LH₂ or liquid nitrogen (LN₂) to that of using LHe for the whole process. From the weight and volume of the cryogenes alone, there is a clear advantage to precooling SIRTf down to 20 K with LH₂. In the hybrid SIRTf, the solid H₂ cools the telescope forward baffle and thermal protection system and is isolated from the He tank and telescope. Cooling these items by H₂ will require plumbing modifications.

Table 3-2 EFFECT OF TWO-STAGE COOL-DOWN

	LHe	LH ₂ -LHe	LN ₂ -LHe
Mass Ratio	1.0	0.38	2.04
Volume Ratio	1.0	0.67	0.44

3.2.6 Replenishment Requirements

Based on these transient cool-down and tank fill thermal analyses, the replenishment requirements of an all-He cooled telescope can be established.

	<u>Range</u>
Cryogen transfer rate (L/h)	100-400
Cryogen venting rate (g/s)	4-16
Dewar/telescope thermal interface at each of two locations (K/W)	0-0.4
Supply tank volume (10^3 L)	6-10
Transfer time (h)	20-160

The timeline and resupply vehicle size and weight are the two most crucial parameters driving the requirements. The allowed time on-orbit to perform the cool-down and fill may be very limited, but a slow efficient cool-down of SIRTf is most desirable to minimize the size and weight of the supply tanks and to eliminate the need to top-off the tanks following the thermal soak-down.

For a system which only requires cryogen replenishment and not cool-down, the cryogen transfer rate can be substantially increased. If the H_2 in a hybrid-solid H_2 /He-II SIRTf is transferred at normal boiling point (1 atm), a 23 percent loss can be expected during the solidification. For a SIRTf H_2 tank of 1650 L, the supply tank would have to be 2800 L of LH_2 . Depending on the lifetime margin of the solid H_2 and the available timeline, a top-off of the tank may be desirable once the cryogen has solidified. The H_2 could also be supplied as a near triple point liquid, substantially reducing the losses in solidification.

3.3 TRANSFER TECHNIQUES

The following cryogen replenishment methods have been investigated to find the one or ones most suitable for LHe transfer: (1) Joule-Thompson devices, (b) mechanical pumps, and (c) fountain-effect pumps. Other techniques were also analyzed briefly.

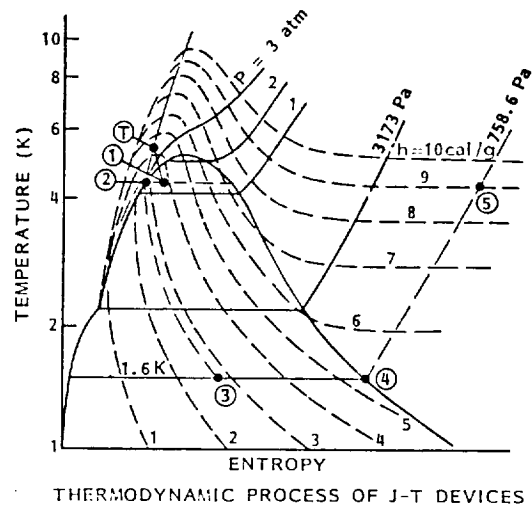
3.3.1 Joule-Thompson (J-T) Device

The use of J-T devices has been investigated in the three possible approaches as shown in the temperature-entropy diagrams of Fig. 3-19. The precooler is assumed to be an ideal counterflow heat exchanger. The transfer line and the SIRTf dewar are assumed to have been chilled down to thermal equilibrium conditions.

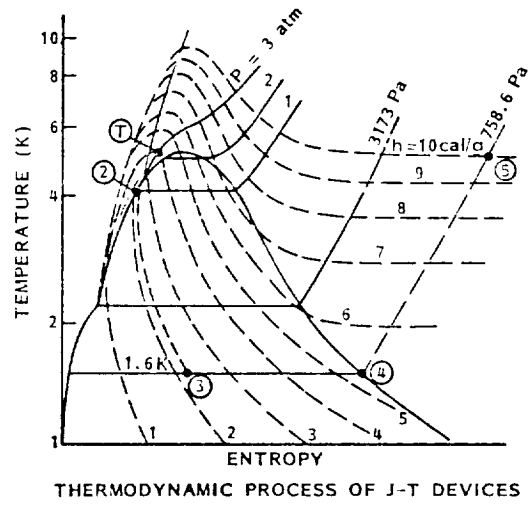
Case (a)

Supercritical helium (ScHe) is blown down isenthalpically to subcritical state. The liquid-vapor mixture is then cooled by vent gas to saturated liquid which is throttled down to 1.6 K and 5.60 torr (758.6 Pa) in the SIRTf He dewar. As shown in Fig. 3-19(a), the liquid yield in the SIRTf dewar is given by

(a)



(b)



(c)

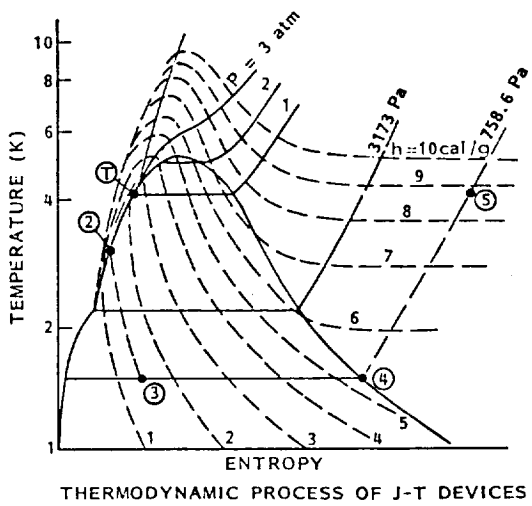


Fig. 3-19 Thermodynamic Process of J-T Devices

$$y_2 = 1 - \frac{\dot{m}_v}{\dot{m}} = 1 - \frac{H_T - H_2}{H_5 - H_4} \quad (3.1)$$

The maximum liquid yield obtainable in this approach is $y_3 = 0.5$ with ScHe supply tank at 5.25 K and 2.3 atm, throttled down to 4.45 K before entering the precooler.

Case (b)

The ScHe is precooled by vent gas at constant pressure in the precooler. This subcooled LHe is then throttled down to 1.6 K and 758.6 Pa in the SIRTf dewar. The liquid yield in this case is given by Eq. (3.1), and the maximum liquid yield obtainable in this approach is $y_3 \approx 0.6$ with ScHe supply tank at 5.25 K and 3.0 atm, precooled to 4.1 K before entering the throttle valve (Fig. 3-19(b)).

Case (c)

Saturated LHe at 4.22 K and 1 atm is precooled by vent gas to a temperature above lambda point, and then throttled down to 1.6 K and 758.6 Pa in the SIRTf dewar. The liquid yield in this case is given by Eq. (3.1), and the maximum liquid yield obtainable in this approach is 0.73 at the lowest T_2 of 3.24 K (Fig. 3-19(c)).

The total amount of He required to fill the 4000-L receiver tank at 4 g/s with 580 kg of 1.6 K He-II in each case is given below.

Supply Tank Cryogen Requirement				
Case	Mass (kg)	Capacity (L)	Supply Tank He	Receiver Tank Vent Rate
(a)	1,160	12,400	5.25 K, 2.3 atm	2.0 g/s
(b)	967	9,140	5.25 K, 3.0 atm	1.6 g/s
(c)	795	6,350	4.22 K, 1.0 atm (LHe)	1.08 g/s

For a transfer rate of 4 g/s, the minimum flow rate of vapor as represented in case (c) would still be 1.08 g/s. The He vapor flow rate of the liquid-vapor phase separator mounted on the IRAS dewar as a function of the tank temperature T is given by (Ref. 1)

$$\dot{m}_v = 0.1046 \times T^{5.9045}$$

For receiver tank temperature of 1.6 K, the vapor flow rate is 1.68 mg/s. The IRAS porous plug is made of sintered stainless steel by Mott Metallurgical

Co., with average pore size of 3.9 μm , thickness of 0.61 cm, porosity 0.27. The open area on the dewar side is 3.5 cm^2 and on the downstream side about 3.0 cm^2 . To accommodate a vapor flow rate of 1.08 g/s at a tank temperature of 1.6 K, more than 640 equivalent IRAS porous plugs will be needed. Furthermore, the above analysis is based on the assumption that the cryogenic condition in the supply tank remains unchanged. In the absence of pressuring devices, the pressure and temperature in the ScHe supply tank will decrease to subcritical states within 30 min with less than 2 percent of the total amount being discharged. Any advantages of using ScHe will also be lost.

Other cryogenic transfer systems should be examined before the J-T system can be seriously considered as a candidate for orbital LHe replenishment. References 1 through 6 listed in section 3.7 present additional information about J-T systems.

3.3.2 Mechanical Pumps

A survey of LHe pumps in open literature indicates that every one is designed to pump normal He. The only one ever tested in He-II was a centrifugal pump driven by a submersible three-phase motor at the National Bureau of Standard (NBS) at Boulder, Colorado (Ref. 7). For STICCRS, use of mechanical pump on normal He with final conditioning by J-T or venting, or on He-II directly, is feasible.

Two types of commercially available LHe pumps are (1) the centrifugal or turbine pump and (2) the reciprocating pump. The drive system can be external at ambient temperature or immersed in LHe (superconducting). The centrifugal pump is generally used for situations where large flow rates are handled with relatively small discharge heads. The reciprocating pump is best suited for smaller flow rates and higher discharge heads.

Major considerations in operating pumps in LHe temperatures are flow stability, reliability, efficiency, and cavitation. An early review in 1973 (Ref. 7) concluded that no centrifugal pumps were commercially available which could be directly and confidently used to pump LHe. Since that time a number of centrifugal pumps as well as reciprocating pumps for use in LHe have been found in the open literature. A literature search has been conducted on the work done to date on LHe pumps. These pumps have been developed for long-life terrestrial use. SIRTf replenishment requires a large-capacity pump to be used in a relatively short operation (under 1000 h). This means less restrictive requirements on bearings and seal lives. The performance characteristics are usually expressed in pressure rise against flow rate at given pump speed in revolutions per minute (rpm), plus some inlet and/or exit conditions.

The state of the art is such that machinery has been developed and built that is capable of pumping LHe in a wide range of capacities. Reciprocating pumps have been built with equal or higher efficiencies than that of centrifugal pumps. Superconductive drive has been used on both reciprocating and

centrifugal pumps. The result of the literature review is given below on pumps for cryogenic He applications.

Reciprocating Pumps with External Drive

Positive displacement devices have been developed to the state where good efficiencies (60 percent – 70 percent) can be achieved (Refs. 8–16). However, they require maintenance (replacement of seals, etc.) and may introduce dynamic pulsations into the pumped stream. These require close fitting parts with resulting high friction losses.

Typical pump characteristics are shown in Figs. 3-20 and 3-21 from pumps built by Gardner Cryogenics (a division of Air Product) and Linde Co. (Munich, Federal Republic of Germany). The Gardner pump (Ref. 13) was tested in 4.2 K, 2.5 atm, up to 16 g/s (420 L/h), intended for use in the Large Coil Program at Oak Ridge National Laboratory. The refrigerator compressor which can handle 300 g/s of ScHe at 3.5 K, 15 atm, was used instead. The pump was loaned to Professor Van Sciver at University of Wisconsin, Madison, to be used in He-II studies.

The Linde pump (Ref. 14) is a three-cylinder, vertically arranged single-acting piston pump with a frequency-controlled three-phase geared motor operating at room temperature. It has a pumping rate up to 4000 L/h and was tested in 4.5-K LHe for more than 560 h with no decline in delivery head and efficiencies. In contrast to the single-cylinder single-acting pump by NTG

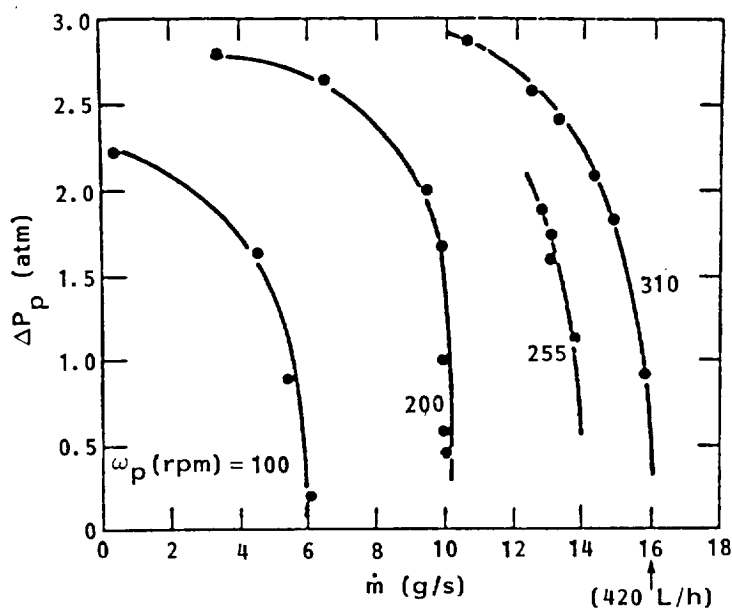


Fig. 3-20 Pump Characteristics. Discharge Pressure = 3.5–7.5 atm; T_2 = 4.2–4.3 K (Ref. 13)

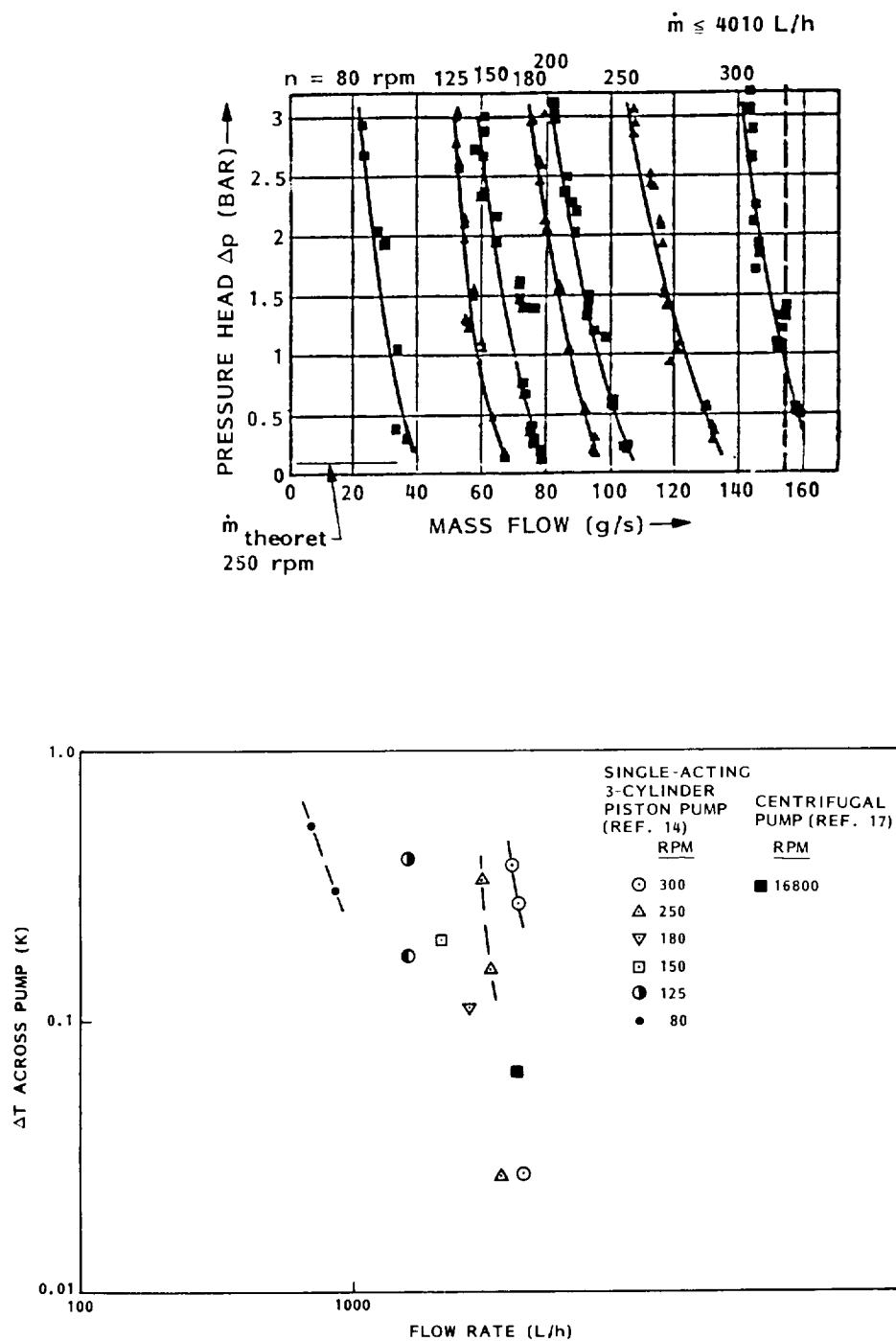


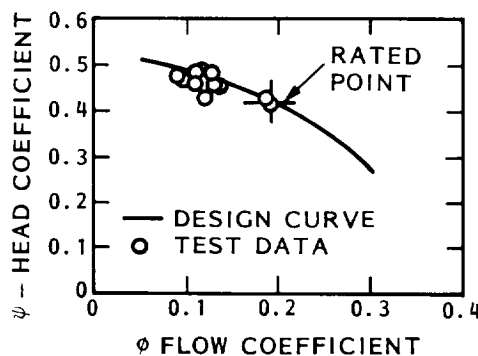
Fig. 3-21 Pump Characteristics $P_E = 4 \text{ bar}$, $T_E = 4.5 \text{ K}$ (Ref. 14)

Nuclear Technik (Ref. 15) also tested at KFK/ITP, the three-cylinder system provides more uniform delivery and flow stability up to 150 g/s (4000 L/h) at a maximum speed of 310 rpm and under the inlet conditions of 4 bars/4.5 K with isentropic efficiency over 62 percent. It is now available commercially. The double-acting bellows-type reciprocating submerged LHe pump developed for NEK's VENUS magnet in Japan (Ref. 16) has been tested for equivalent of 3000 h. It has a capacity of 900 L/h and low heat generation (about 0.2 W). However, it is not commercially available. Table 3-3 summarizes these LHe reciprocating pumps with external drive.

Centrifugal Pumps with External Drive

Centrifugal pumps have been developed to the state where reasonable efficiencies (50 to 60 percent) have been achieved (Refs. 17-21). Ball bearings in fiberglass/teflon cages have been successfully used in limited-life, limited-speed applications. Because of the high speeds required for centrifugal pumps, gas bearings are favored for long life. These have negligible bearing friction losses, but need long tubular stainless steel shafts.

Typical performance characteristics are given in Fig. 3-22 for pumps built by Creare (Ref. 17). These have the required pumping rates and have the potential for the SIRTf replenishment operation.



SWIFT, et al. (1982)
BUILT BY CREARE R&D FOR
BROOKHAVEN/ISABELLE
 $\dot{m} \leq 3925 \text{ L/ln}$

$$\psi = \Delta p / \rho U_2^2$$

$$\phi = \dot{m} / U_2 A_2$$

Δp = PRESSURE RISE ACROSS THE PUMP

\dot{m} = MASS FLOW RATE THROUGH THE PUMP

ρ = FLUID DENSITY

U_2 = TIP VELOCITY OF THE IMPELLER AT ITS EXIT

A_2 = EXIT AREA OF THE IMPELLER

Fig. 3-22 Performance of Centrifugal Pump (Ref. 17)

Table 3-3 LHe RECIPROCATING PUMPS WITH EXTERNAL DRIVE

Reference	Pump Characteristics	Remarks
Schuck (1975) Gardner Cryogenics	≤ 40.5 g/s (1240 L/h) of saturated LHe at 1.36 atm, $\Delta p \sim 1$ atm, no thermal acoustic oscillation (TAO) observed $\eta_s \sim 0.7$ piston dia. = 11.4 cm	Pump delivered for Fermi Energy Doubler project with flow range of 10-120 g/s
Hartwig et al. (1978)	≤ 500 L/h at $\Delta p = 1$ atm. double-acting plunger type piston rings of Teflon-impregnated bronze material, cylinder dia. = 3.2 cm, stroke = 2.7 cm, 400 RPM, DC shunt motor	Pump built by Linde, Munich under license from Siemens, for KfK/FRG; 15 pumps built in 1970-1978
Burns et al. (1980) LBL	≤ 50 g/s, double-acting bellows of 10.8-cm ID, driven by var. speed, torque controlled DC gear motor/ecc. cam shaft	Built in-house for LBL/TPC experiments
Lue et al. (1982) Oakridge NL	≤ 16 g/s (120 L/h) at 333 rpm, $\Delta p \leq 1$ atm. $\eta_s = 0.50-0.76$ without consideration of heat leak down support structure SCR - controlled motor	Pump built by Gardner (but not used) for Oak Ridge NL/Large Coil Program
Kraft (1982) Huebner et al. (1984) KfK/ITP	≤ 4500 L/h at $\Delta p = 1.5$ atm, single-acting, piston dia. = 6cm stroke = 5 cm, $\eta_s = 0.5 - 0.6$	Built by MTG - Nukleartechnik, FRG, very unsteady delivery over 50 g/s (1500 L/h); safe under 150 rpm only
Lehmann Mingos (1984) KfK/ITP	≤ 4010 L/h at 4.5 K, 4 atm, 3 single-acting cylinder driven by 3-phase 2.2-kW geared motor $\eta_s \geq 0.62$	Built by Linde for European Large Coil Test (LCT) Facility/Oak Ridge
Kamioka (1984) KEK NL/Japan	800 L/h by double-acting bellows pump actuated by air/oil cylinder at $\Delta p \leq 4$ atm. Pump OD = 19 cm, height = 28 cm, air pressure = 5 atm, $Q_p = 0.2$ W, $Q_{shaft} = 0.8$ W, $W_f = 42.33$ W	Built in-house for KEK NL VENUS detector magnet; used basic design of Burns et al. (1980)

A centrifugal pump with a "magnetic clutch" system has been proposed by Professor T. H. K. Frederking of the University of California, Los Angeles. The ingredients of the system are given below, followed by a schematic drawing of the pump (Fig. 3-23):

- Warm DC drive motor, DC permanent magnet, bearings degreased with operation near 100 K (300 K is acceptable in principle)
- Shaft from motor to low temperature: stainless steel tube, supercritical speed, attached at its warm end to the motor and at its cold end to the drive magnet
- Magnet system: Alnico, but cobalt samarium has a higher force
- Magnet bearing: (inside He-II fluid space) teflon body with many holes for fluid access
- Pump rotor: plastic wheel attached to driven magnet inside fluid space

New magnets based on rare-earth neodymium alloyed with iron and boron (NdFeB) have been found to be stronger and cost less than the best samarium-cobalt magnets (Ref. 18). Sealless magnetic drive pumps are also available from March Manufacturing Inc., Glenview, Illinois, but they have never been used in cryogen fluids.

Centrifugal Pumps with Submerged Drive

The NBS centrifugal pump with submerged drive was operated successfully by McConnell to pump He-II (Ref. 17). Additional work was done by Ludtke

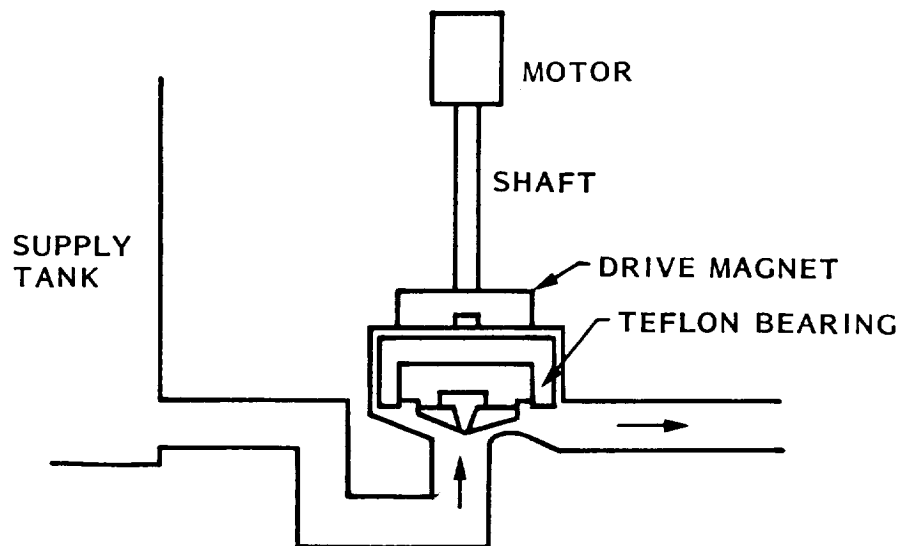


Fig. 3-23 Centrifugal Pump with Magnetic Clutch (Frederking, UCLA)

(Ref. 22) and Van Arend et al (Ref. 23). A new cryogenic motor was also tested recently by Ruppert et al (Ref. 24). Typical pump characteristics are shown in Fig. 3-24.

The major advantages of using a drive completely submerged in LHe are compact design, no need of cooling, no rotating shaft seal and leakage problem, no external insulation, no space requirement, and no force-transferring parts between 4.2-K and room-temperature drives. The centrifugal pump with a submerged drive was operated successfully to pump He-II by McConnell (Ref. 7) and normal He by Ludtke (Ref. 22) at NBS Laboratory. It was run without cavitation danger and other special He-II problems. One system developed at the Fermi Laboratory (Ref. 23) using a commercial centrifugal pump for larger capacity (up to 38 g/s) showed such poor performance that it was replaced by a reciprocating pump with external drives. A new cryogenic motor was also tested recently by Ruppert, et al. (Ref. 24). The NBS pump has a capacity up to 1000 L/h of He-II between 1.85 K and 1.95 K. This can be directly applicable for SIRTf, and further design analysis should be pursued.

Table 3-4 summarizes these LHe centrifugal pumps with external and submerged drive. The one built by Creare is available commercially and has the potential for SIRTf replenishment operation.

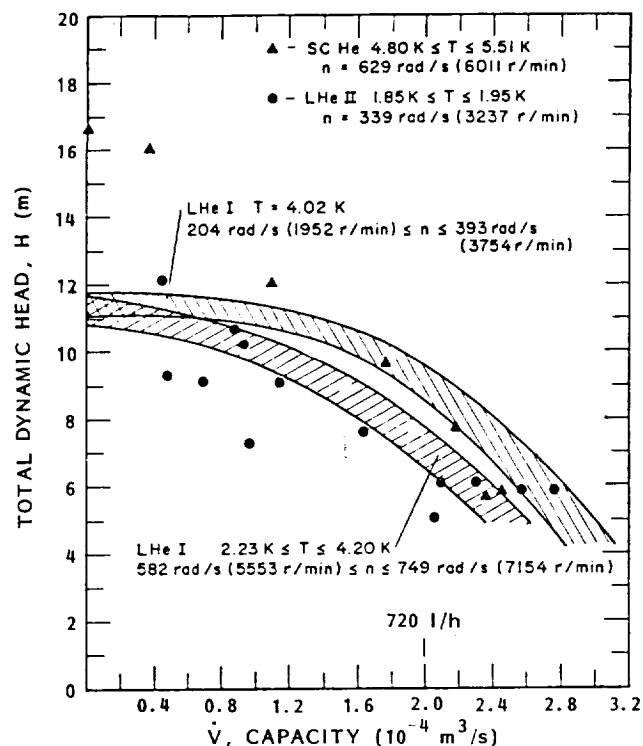


Fig. 3-24 H- \dot{V} Data Normalized to the Design Speed, 628 rad/s (6000 rpm) (Ref. 7)

Table 3-4 LHe CENTRIFUGAL PUMPS WITH EXTERNAL DRIVE

Reference	Pump Characteristics	Remarks
Swift et al. (1982) Creare	<157 g/s (3925 L/h) $P_i = 5$ atm, $T_i = 4$ K Brushless DC motor with gas lubricated and magnetic bearing, $W_p = 60$ W, $\Delta P = 0.33$ atm, $\eta_s < 0.65$	Built by Creare R and D, Hanover, NH for Brookhaven NL/ISABELLE cooler; too large for STICCRS
Frederking (1984) UCLA	Alnico magnet/plastic wheel driven by DC motor	Proposed for transfer of He-II at $T < 2.172$ K
Swift et al. (1984)		Review
Sixsmith et al. (1970)		Review
Guttzmann (1960)	First reported attempt to pump LHe used a single stage, centrifugal force pump to provide adequate head to LHe entering a reciprocating, high-pressure close-coupled, canned electric motor immersed in LHe	
McConnell (1973)	<1000 L/h of LHe-II at 1.85 K $< T < 1.95$ K and ScHe 4.8 K $\leq T \leq 5.51$ K with 3-phase var. speed motor submerged $\eta_s \leq 306$	No degradation in performance due to cavitation even at $P_i < P_{sat}$
Ludtke (1975)		
Vander, Arend, et al. (1975)	<35 g/s (860 L/h) at $\Delta p \sim 0.5$ atm; Used commercial 3-stage centrifugal pump driven by 400-Hz induction motor immersed in LHe $W_{Total} \sim 54$ W	Poor performance led to replacement by reciprocating pump for Fermi Energy Doubler Project (Schuck, 1975)

Superconducting Pumps

The use of an electrically operated LHe pump was considered primarily because of simplicity of flow control. A small unit built at MIT (Ref. 25) obtained flow rates up to 25 L/h. Another small pump capable of transferring $6.94 \times 10^{-6} \text{ m}^3/\text{s}$ with a discharge head of 0.92 m and $3.3 \times 10^{-6} \text{ m}^3/\text{s}$ at a 1.83 m head is reported by Darrel and Schoch (Ref. 26). The pump is 2.22 cm in diameter and 5.08 cm long. As shown in Fig. 3-25, a superconducting niobium piston, suspended by a thin-wall nickel bellows, is forced to oscillate at a resonant frequency of 120 Hz by 60-cycle current flowing through a superconducting coil located below the piston. The flow rate could be adjusted by varying the amplitude of the coil current. The mass of the piston (armature) and the bellows spring constant were selected to produce resonance at this frequency. When the piston moves upward, hydrodynamic forces cause the suction valve to close and the discharge valve to open, forcing liquid through the outlet tube. These valves are disk-type and made of 0.015-in. thick nylon. In reciprocating pumps, the geometry and spring design of disk-type inlet valves can affect the cavitation performance.

The reliability of this pump depends primarily on the life of the bellows, which is not well known. The leakage rate past the valves and hence the volumetric efficiency is not reported. These could be severe problems in pumps of larger size. Considerably more testing of this type of pump is needed before a true evaluation of its merits can be given.

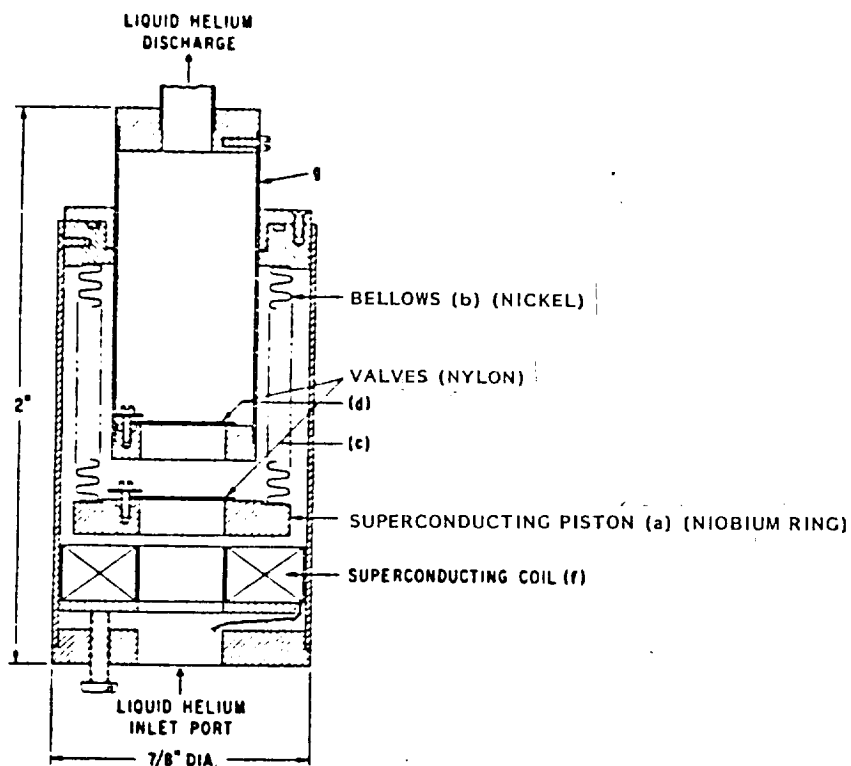


Fig. 3-25 Superconducting Pump Cross Section (Ref. 26)

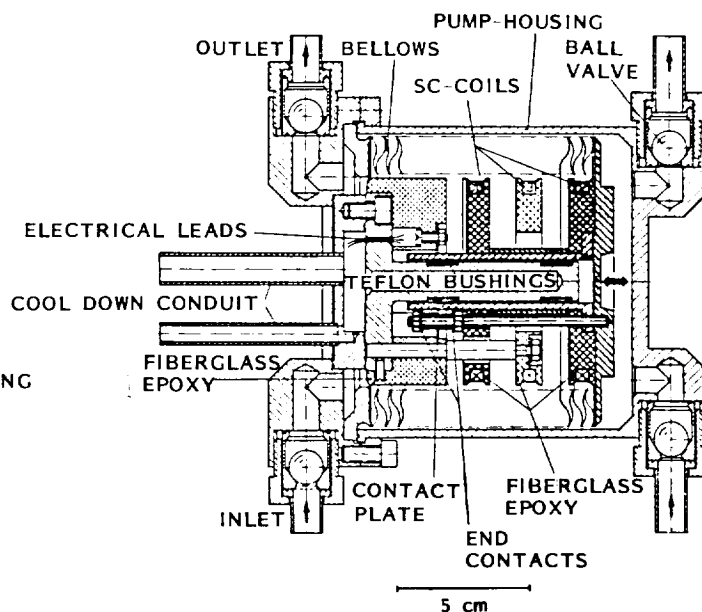
The Italian system of Rivetti et al. (Ref. 27) using a centrifugal pump of NBS design was for the study of flow meter behavior. The mass flow rate was not measured. Figure 3-26 shows a double-acting bellows pump built by Schmidt (Ref. 28) in Kernforschungsventrum Karlsruhe, Federal Republic of Germany, which delivered up to 155 L/h at 4.2 K, 4 bar, $\Delta P = 0.1$ atm for a pump frequency of 0.6 Hz. An upscaled version of a three-coil arrangement and piston cross section of 200 cm² (8-cm radius) and a stroke of 5 cm would give a pressure difference of 4 bar in mid-section and a pumping rate of 7200 L/h for a pump frequency of 1 Hz. These are not yet available commercially. Table 3-5 summarizes LHe pumps with superconducting drive.

A large number of LHe pumps are available commercially. For STICCRS mission, the pumps that operate in the required capacity (up to 4000 L/h) are given in Table 3-6. None of these has been tested in He-II. However, there are no obvious problems in adopting these pumps for STICCRS operations. The centrifugal pumps have higher efficiency for continuous high-capacity flow with smaller discharge heads. The reciprocating pumps provide higher discharge heads at smaller flow rate. Both types with drives should be investigated further in any future studies.

3.3.3 Fountain Effect Pumps

A fountain effect pump (FEP) uses a unique property of He-II called the fountain effect, or thermo-mechanical effect, in which a mass flow is produced

- DOUBLE-ACTING BELLOWS PUMP
- THREE IDENTICAL SUPERCONDUCTING COILS
- $\Delta P = 200$ mb (150 torr) AT
360 l/h OF 4.2 K LHe
LOSSES ~ 2 W
- COMPACT AND NO FORCE TRANSFERRING PARTS BETWEEN 4.2 K AND 300 K



CROSS SECTION OF THE HELIUM PUMP. STAINLESS STEEL PIECES ARE HATCHED, FIBERGLASS EPOXY PIECES ARE CROSS-HATCHED. (SCHMIDT, 1984)

Fig. 3-26 Double-Acting Bellows Pump With Magnetic Drive System (Ref. 28)

Table 3-5 LHe PUMPS WITH SUPERCONDUCTING DRIVE

Reference	Pump Characteristics	Remarks
Kolm et al. (1965)MIT	<23 L/h, double-acting stainless steel piston 1.91-cm dia. x 1.59-cm stroke. Alnico magnet (armature) with 2 copper solenoids in LN	First system of monel bellows actuated by iron armature/superconducting coil failed
Darrel, et al. (1965) GE	< 25 L/h, overall 2.2-cm dia x 5.08-cm length, piston of niobium ring suspended by nickel bellows, nylon disc valves, superconducting coil in LHe $Q_{LHe} \approx 0.37$ W, pump loss ≈ 0.04 W, thermistor liquid level sensor loss ≈ 0.1 W	Funded by NASA contract NAS8-2418
Rivetti et al. (1982)	$m \leq 400$ L/h (not measured) at 4.2-8 K. Used NBS design of centrifugal pump driven by 3-phase asynchronous AC motor at 30-100 Hz, 3 different cyl. rotors $W_p \sim 1$ to 2 W	For study of flow meter behavior; will test in He II in 1985
Schmidt (1984) KfK/FRG	< 155 L/h at 4.2 K, 4 bar, $\Delta p = 0.1$ atm, 36 rpm Double acting bellow pump with 4 ceramic ball valves fit in stainless steel faces, teflon bushings. Magnetic drive consists of 3 identical superconducting coils. $A = 73$ cm ² , $L = 1$ cm ≤ 7200 L/h in upscaled design ($A = 200$ cm ² , $L = 5$ cm)	For European Large Coil Test (LCT) conductor test facility

*Low flow (≤ 25 L/h) types like superconducting piston or diaphragm pumps using forces between superconducting coil and a diamagnetic (superconducting) or ferromagnetic material have been built by Kolm et al (1965) at MIT and Darrel et al (1965) at GE, Schenectady, NY

Table 3-6 COMMERCIALLY AVAILABLE LHe PUMPS

	CREARE R and D Inc. Swift et al (1982) Brookhaven/Isabelle	Kraft (1982) Huebner et al.	KFK/FRG Lehman and Minge (1984) European LCT Coil	Schmidt (1984) European LCT Conductor	GE, Schenectedy, NY Darrel et al. (1965)
	Centrifugal pump	Single-acting piston pump by NIG-Nukleartechnik, Linde, Munich, FRG, + Gelnhausen, FRG	3-cylinder single-acting piston pump, 5-cm dia 4.7-cm stroke parallel, 120° dephased pistons	Double-acting bellow Pump with 4 ball valves d ~ 9.64 cm (16) Stroke 1 cm (5)	Single-acting nickel bellow with niobium ring, nylon valve Overall dia = 2.22 cm Stroke = 5.1 cm
Pump	Impeller O.D. = 2.7 cm gas lubricated journal and magnetic thrust bearings	6 cm stroke 5 cm stroke			
	(1984/DOE)				
P _i (atm)	4.67 (4.67)	3-5	4	4	1
T _i (K)	3.925 (4.5)	4-5	4.5	4.2	4.2
P _i (atm)	5.0 (5.0)		4.5-7	Δp ~ 0.22 atm (4)	
T _e (K)	3.989				
W _p (W)	60		2.2 kW	(2)	
Q (W)					
m (g/s)	157 (160)	up to 150	up to 150		
V (L/h)	3925	up to 4500	up to 4010	360 (7200)	up to 25
N (rpm)	16800 (16700)				
η _s	0.65 0.65	0.5-0.6	>0.62		
Drive	External brushless DC motor with adjustable speed control	External DC motor	External 3-phase 2.2-kW geared motor with speed control up to 310 rpm	3 identical superconducting coils 1 fixed to pump housing, 2 in series, to below	Superconducting oscillating solenoid

*Other pump manufacturers include Gardner Cryogenics - piston pump up to 3500 L/h for Fermi NAL (Schuck, 1975), Oakridge NL (Lue et al., 1982), Kamioka (900 L/h)

+ Linde and Siemens workshops built 15 double-acting pumps (1970-1977) for flow up to 17 g/s (500 L/h)

() proposed design

through a porous plug by a temperature gradient across the plug. The liquid flows from the cold side to the warm side of the plug. It has the advantage of no moving mechanical part subject to forces. Use of this fountain effect has been demonstrated by small laboratory setups for all kinds of purposes. It has also been used successfully as a vapor-liquid phase separator (VLPS) in zero-g. Although a review of research efforts on VLPS was given by Schotte (1984), aside from a few notable exceptions, quantification seems to be absent. Therefore, considerable care has to be exercised for a safe design which will accomplish both volumetric flow rates required and pressure differences needed.

Compared to VLPS plugs, the FEP plugs have usually been in a different pore size range. The VLPS plugs tested have started with sizes as high as $10\text{ }\mu\text{m}$ (nominal size of particle retention), going down to $0.5\text{ }\mu\text{m}$. The FEP plug needs not only a small pressure difference associated with a small temperature difference across the plug, but also enough reserves built in such that overloads do not bring the pump instantly to the static limit of maximum pressure difference. Therefore, both a small particle size and a small porosity appear to be desirable for an optimum design.

The pressure-temperature diagram of the two laboratory-demonstrated systems - the heater-activated (Leiden-type) and the cooler-activated (Klipping-type) FEP - are shown in Fig. 3-27. The insert (a) of Fig. 3-27 shows a simple scheme for the Klipping pump, and insert (b) sketches a Leiden pump. A

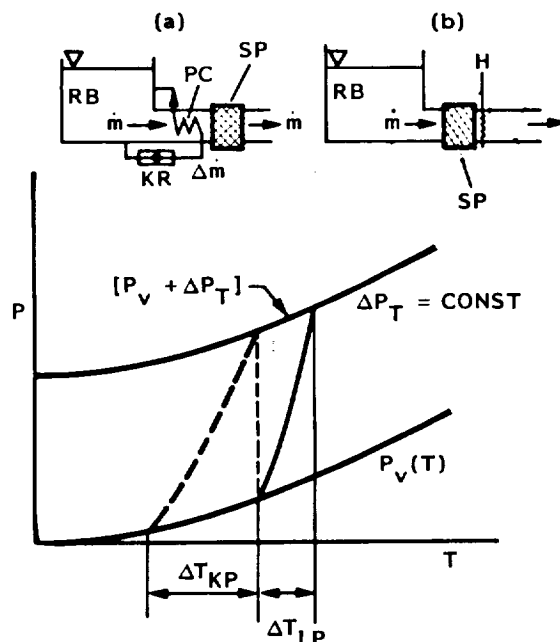


Fig. 3-27 Pressure-Temperature Diagram with State Changes in FEP: (a) Klipping-Type Pump for Steady Flow of Liquid; (b) Leiden Pump with Heater

specified pressure difference ΔP is assumed in order to compare pump performance quantities. Thus, the pumps in Fig. 3-27 supply the same $\Delta P_T = \Delta P$, and the ultimate pressure is shifted by a constant P -change with respect to the vapor pressure curve $P_V(T)$. The Klipping pump is characterized by a required ΔT_{KP} , and the Leiden pump needs ΔT_{LP} .

The fountain pressure difference is

$$\Delta P_T = \int_T^{T + \Delta T_{LP}} \rho S(T) dT \quad (3.2a)$$

for Leiden pump and

$$\Delta P_T = \int_{T - \Delta T_{KP}}^T \rho S(T) dT \quad (3.2b)$$

for Klipping pump. As the entropy is a monotonically increasing function of T , Eqs. (3.2) imply a larger ΔT for the Klipping pump than for the Leiden pump. In the Klipping pump system, a liquid pre-cooler (PC) is operated by means of a refrigerator (KR). At least two techniques are available to produce this cooling. One consists of venting the supply tank to space to produce evaporative cooling. This approach is straightforward in principle and can produce the required cooling with a small evaporation loss. The vacuum of space provides a convenient and sufficient pump.

A second approach, more complex, requires the use of a vortex refrigerator (Ref. 31). A vortex refrigerator as shown in Fig. 3-28 consists of two chambers A and B and a heat exchanger W connected to each other by the superleaks S_1 and S_2 . It is mounted on the bottom of the He cryostat which contains LHe at a temperature below the lambda-point, e.g., $T = 1.5$ K (Fig. 3-28).

The working principle of the apparatus can be described as follows. Chamber B is heated electrically to 1.7 K. This converts superfluid into normal fluid. The normal fluid can only be discharged gradually through the capillary C_2 to the heat exchanger W, so if the heater in chamber B is switched on, a flow of normal fluid from vessel B to the heat exchanger is created. In the heat exchanger, the normal fluid is converted again into superfluid, which can flow through superleak S_1 , chamber A, and capillary C_1 to the main He reservoir in the cryostat.

The velocity of the superfluid in capillary C_1 is so high that vortices are created in the superfluid, setting up pressure gradients which push the normal fluid away from chamber A. Since no normal fluid is supplied to A via S_1 , and normal fluid is carried away from A through C_1 to the main He reservoir

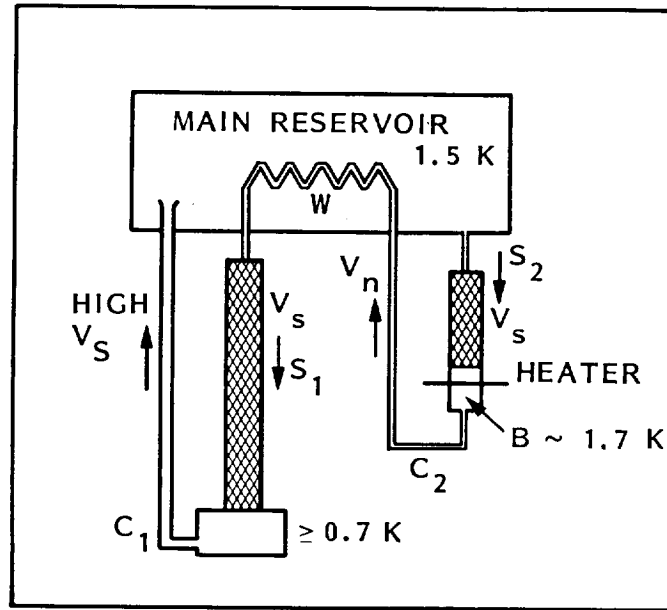


Fig. 3-28 Cooling Device Without Moving Parts (Ref. 31)

(heat flow through C_1 to the main He reservoir), heat is extracted from chamber A.

The temperature of A can be set between 0.7 K and the temperature of the main He reservoir by varying the amount of heat supplied to vessel B. Cooling capacities for capillaries C_1 of different diameter are shown in Fig. 3-29 (0.5-, 1-, and 2.4-mm diameter), where the temperature of chamber A is plotted as a function of the heat load in the chamber (full lines). These curves are independent of the choice of capillary C_2 and of the bath temperature. The dotted curves are calculated from the flow characteristics of the normal fluid in capillary C_1 .

A constant mass flow rate (\dot{m}) is supplied from a He-II bath (RB) during steady flow of liquid through the porous plug (SP) of the pump. The Leiden pump has a heater (H) downstream of the plug (SP). Introducing a power law approximation for the entropy, $S \sim T^\alpha$, one obtains thermal energy needed for each thermopump as $Q = \alpha(\Delta P_T/\rho)$. As shown by Yuan et al. (Ref. 32), for an arbitrary ΔT the additional work per mass of the Klipping pump is obtained as

$$\dot{W}/\dot{m} = \alpha(\Delta P_T/\rho)[(T - \Delta T)^{-1} - T^{-1}]T_e \quad (3.3)$$

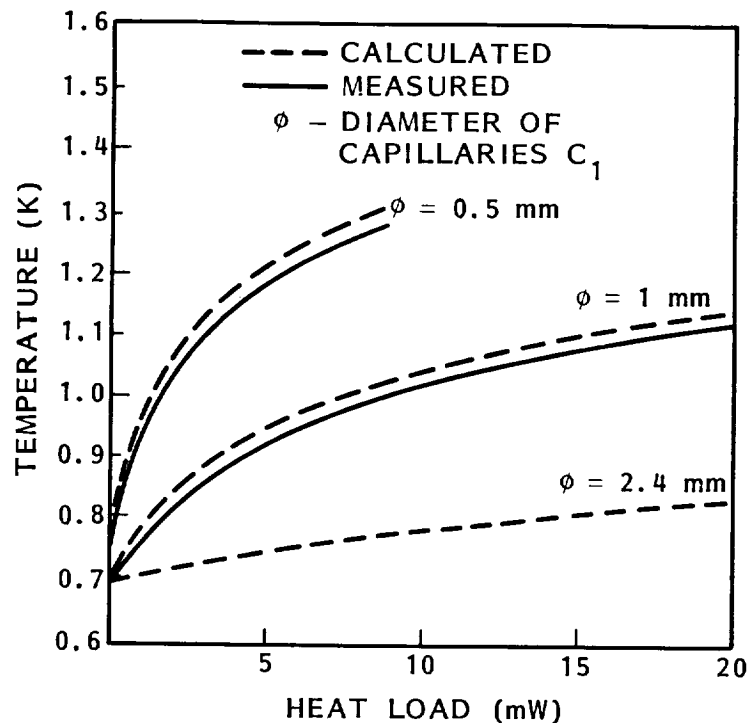


Fig. 3-29 Temperature of Chamber A Versus Heat Load in Chamber A Independent of C_2 Size and T_{main} (Ref. 31)

where T_e is the ambient temperature. In the related (W/m) equation for the Leiden pump, a lower numerical value results because of a generally higher temperature.

Thermodynamic analysis of LHe transfer by FEP between two tanks will be discussed in Section 3.5. Design of the Leiden-type and Klipping-type pumps to satisfy the mass flux in conjunction with the required plug cross section is described below.

3.3.3.1 Heater-Activated FEP (Leiden-Type). The simplest FEP system may be the heater-activated pump without aftercooler. In this case, only two parts are major design items: the porous pump body and the heater unit.

In the design of a porous plug, the major parameters are: (a) temperature difference across the plug, which is determined by the heat input and the thermal conductance of the plug material and the He within the pores; (b) pore size and length, which determine the relative strength of the thermomechanical effect and the pressure gradient effect; (c) total plug cross-sectional area which, with pore size and length, determines the total flow of He possible for a given temperature gradient, and (d) porosity.

At low speed below the critical pressure, there is ideally zero pressure difference. As soon as finite pressure differences are required, the pump

conductance speed ($v_0/\Delta p$) has to be reduced to finite values. As critical superfluid velocity is exceeded, vortex shedding takes place and produces a vortex flow resistance. This increases with speed v_0 until the classical flow characteristics of Newtonian flow is reached. To be on the safe side, the critical velocity is used as the basis.

The critical transfer rate, or the critical superfluid velocity $v_{sc} = v_{op}/\rho_s$ in $\text{cm}^3/\text{cm}^2\text{-min}$ has been published. For the Leiden FEP-body, the critical transfer rate is given in Fig. 3-30. The value of v_{sc} for 0.7- μm pore size (normal particle size of retention filtration) below 1.5 K is equivalent to 72 $\text{L}/\text{cm}^2\text{-h}$. The required cross section can be easily obtained as the ratio of the required maximum flow rate and the critical transfer rate. To be safe, packed-powder units may be used in parallel (Fig. 3-31). The individual units must have lateral vacuum insulation (Fig. 3-32). They are conveniently suspended from a base plate. If large cross section is required, an alternate candidate is the Surfamax manufactured by Pall Corporation (Fig. 3-33).

Transport in porous plugs in general is very complex. The low-temperature research has shown that there exist several asymptotic functions which provide valuable guides for He-II transport description, e.g., the zero net mass flow mode. Thus, the coverage of room-temperature phenomena all the way down to the lambda transition and the He-II transport rates may be considered within a

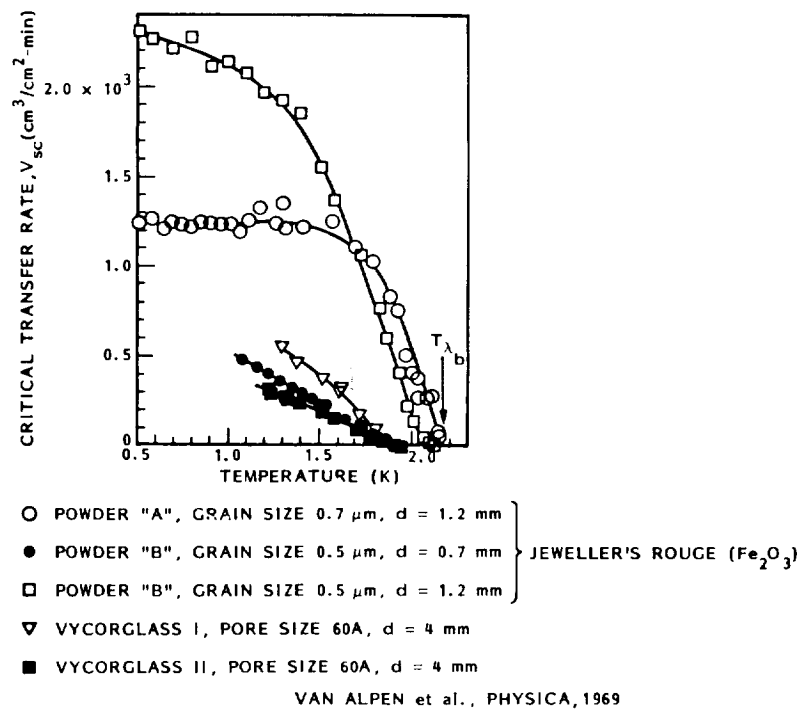
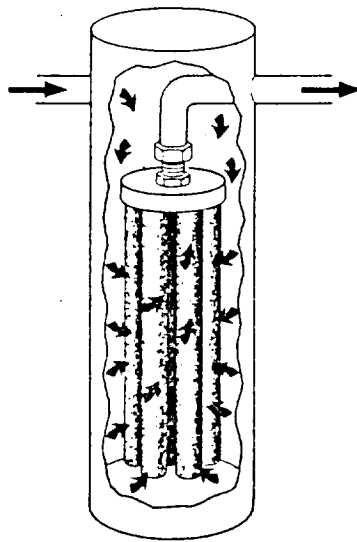


Fig. 3-30 Critical Transfer Rate V_{sc} as a Function of Temperature for Different Powders



DESIGN PROPERTIES: PORE SIZE, PERMEABILITY,
LARGE SURFACE AREA
FUNCTION: EXTENDED AREA FILTRATION

Fig. 3-31 Parallel Units (Mott Metallurgical Corp.)

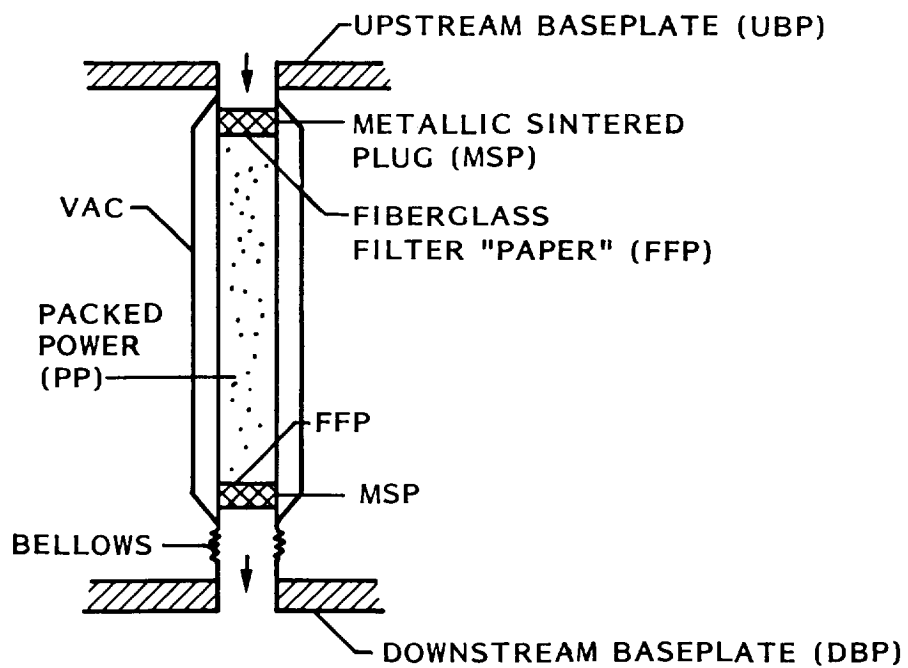


Fig. 3-32 Leiden-Type Cartridge Design (Vacuum Jacket Individually Arranged)

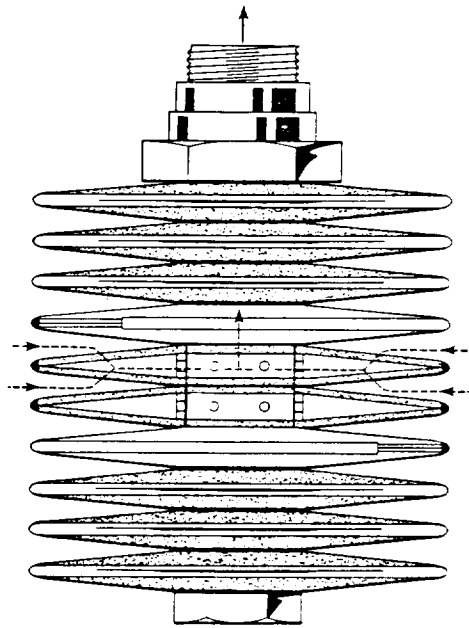


Fig. 3-33 Surfamax of Pall Corp. (Fluid enters from above and below individual sections, passes through the porous media, and exits through an internal core.)

common frame of reference. For the present purpose, Darcy's law of fluid flow through porous media is used as the basis. The classical Darcy law gives the volume flow rate per total cross sectional area by use of the Darcy permeability K_D

$$v_0 = \frac{1}{A} K_D \nabla P / \eta \quad (3.4)$$

Permeability of several porous plugs has been measured at UCLA (Ref. 33) as a function of temperature, as shown in Fig. 3-34. Similar measurements on porous stainless steel plugs were also made at University of Alabama at Huntsville (Ref. 34).

For the present study, in the vortex flow resistance regime (between the superflow and the Newtonian flow), the permeability ratio K_{II}/K_D is considered for a tie-in with Darcy convection of Newtonian fluid. In this regime, the power law approximation yields the ratio by (Ref. 32)

$$\frac{K_{II}}{K_D} = C^{-4} \left(\frac{\rho_s}{\rho} \right)^4 (\rho v_0 L_c / \eta_n)^{-3} \quad (3.5)$$

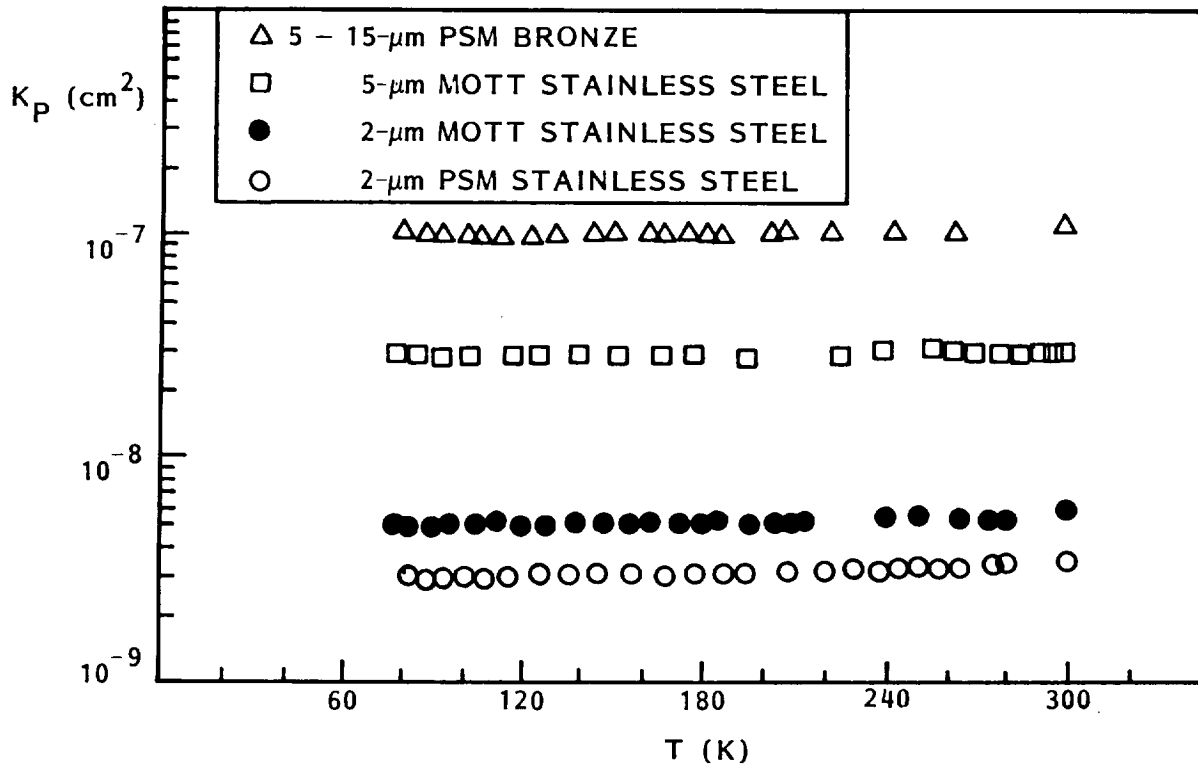


Fig. 3-34 Darcy Permeability Versus He Gas Temperature (Ref. 33)

where

$$C = 0.56 \pm 0.04$$

$$L_c = K_D^{1/2} \text{ is the throughput or characteristic length}$$

The He-II volumetric flow rate per total plug cross section can be related to K_D by the power law approximation proposed by Voté et al. (1971)

$$V_o = \frac{\dot{V}}{A} = \frac{\rho_s}{\rho} \frac{1}{c} \frac{\eta_n}{\rho L_c} \left[\frac{\rho \nabla P L_c^3}{\eta_n} \right]^{1/4} \quad (3.6)$$

The permeability ratio for various bath temperatures of a 1-μm plug with $K_D = 2.5 \times 10^{-12} \text{ cm}^2$ is shown in Fig. 3-35 (Ref. 32). The pressure gradient across the plug at given temperature can be obtained from Eq. (3.6) as a function of the volumetric flow rate per total plug cross section.

The power requirement of the heater can now be estimated for a porous plug with given pressure gradient. An example is given for a porous plug with a reference pressure difference of 50 mbar (3.65 torr) at a flow rate of 1000 L/h. It is noted that the estimated pressure drop for 1000 L/h in the flight experiment proposed by DiPirro (1984) is 55 mbar. The mechanical flow

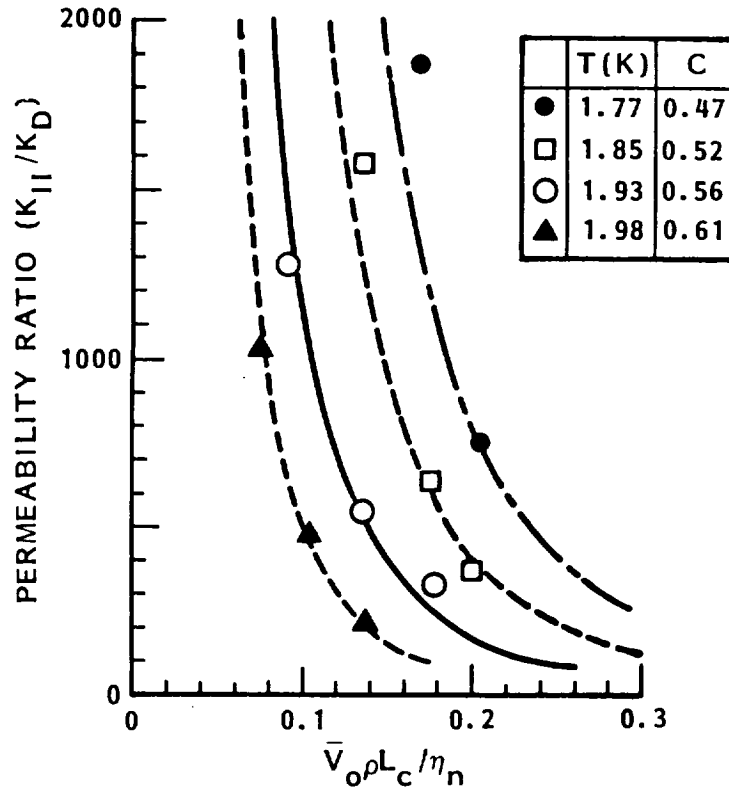


Fig. 3-35 Permeability Ratio for Various Bath Temperatures of a 1- μm Plug with $K_D = 2.5 \times 10^{-12} \text{ cm}^2$. (Ref. 32)

power is the product of the volumetric liquid flow rate V_L and the pressure differences ΔP

$$W_F = \dot{V}_L \Delta P \quad (3.7)$$

Assuming a user characteristic with $\Delta P \propto V_L^2$, the mechanical flow power is scaled by

$$\frac{W_F}{W_{\text{ref}}} = (\dot{V}_L / \dot{V}_{\text{ref}})^3 \quad (3.8)$$

The heat supplied to liquid He-II in a Leiden-type pump is calculated using the power law approximation for the entropy

$$C_p = 5.6 \times S(T) \quad (3.9)$$

The heat flow rate to the liquid is

$$\dot{Q}_{II} = \dot{m} \int_T^{T + \Delta T} c_p(T) dT = 5.6 \dot{m} \int_T^{T + \Delta T} S(T) dT \quad (3.10)$$

Since $\frac{\Delta P_T}{\rho} = \int_T^{T + \Delta T} S(T) dT$, Eq. (3.10) becomes

$$\dot{Q}_{II} = 5.6 \times \frac{\dot{m}}{\rho} \cdot \Delta P_T = 5.6 \times \dot{V}_L \Delta P_T = 5.6 W_F \quad (3.11)$$

Consequently, the thermal power for the liquid He-II, excluding Kapitza temperature drop, is just 5.6 times the mechanical flow power needed for the liquid He-II. The power \dot{Q}_{II} and the pressure difference with associated fluid temperature difference required for the He-II transfer are plotted in Fig. 3-36.

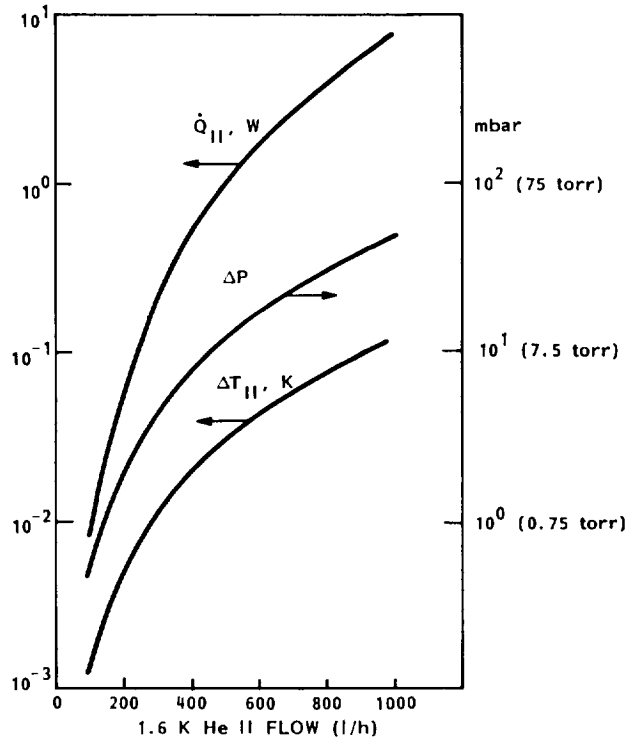


Fig. 3-36 Power Input to He-II and He-II Temperature Pressure Difference Required for Leiden-type FEP

With an overall empirical transmission coefficient (Challis type) of 0.1, the heat to be supplied, via the heater, to He-II is

$$\dot{Q}_{II} = \dot{Q}_K = A_K \dot{q}_K = 0.1 A_K \cdot \dot{q}_{\text{theo}} \quad (3.12)$$

The Kapitza heat flux density q_K (power per Kapitza surface area) is

$$\dot{q}_K = 0.1 \sigma_{BB} \left[(T + \Delta T_K)^4 - T^4 \right] \quad (3.13)$$

where σ_{BB} is the black body phonon emissivity for the material under consideration. T is the bath temperature (taken as the supply tank temperature) and ΔT_K the Kapitza temperature difference. The blackbody σ_{BB} can be scaled from (Ref. 35)

$$\sigma_{BB} = \sigma_{\text{ref}} \left(\frac{\theta_{\text{ref}}}{\theta_b} \right)^2 \left(\frac{V_{m,\text{ref}}}{V_{m,b}} \right)^{2/3} \quad (3.14)$$

The reference values are assumed as follows:

$$\begin{aligned} V_{m,\text{ref}} &= 1 \text{ cm}^3/\text{mol} \\ \theta_{\text{ref}} &= 1 \text{ K} \\ \sigma_{\text{ref}} &= 1/4 (1.93 \times 10^5) \text{ W/cm}^2\text{-K}^4 \end{aligned}$$

For copper with Debye temperature of 340 K, and $V_{mb} = 7.1 \text{ cm}^3/\text{mol}$, the blackbody phonon emissivity calculated from Eq. (3.13) is $0.113 \text{ W/cm}^2\text{-K}^4$. The Kapitza heat flux density can now be computed from Eq. (3.13). The Kapitza heat transfer area required is calculated from Eq. (3.12), and plotted in Fig. 3-37 for bath temperature of 1.6 K. In general, most heater-activated laboratory units appear to have been operated as small units for a limited time, i.e., in batch operation. Little appears to be known about steady flow through the device. Additional experimental data and theoretical analysis are needed.

3.3.3.2 Cooler-Activated FEP (Klipping-Type). Based on Eq. (3.1), the Klipping-type FEP appears to be inferior (requires larger ΔT) to the Leiden-type FEP. But in principle, for a certain set of conditions, no additional power is required in space as vacuum is available outside. Only the work to move a valve position is needed. This leads to a lowering of the supply tank temperature with small loss of cryogenics. With no flow other than the vented vapor, the volume fraction loss in evaporative cooling of liquid from initial temperature T_i to final operating temperature T_f is given by (Ref. 36)

$$\frac{\Delta V}{V} = 1 - \frac{\rho_i}{\rho_f} \exp \int_{T_i}^{T_f} \frac{c_p}{\lambda} dT \quad (3.15)$$

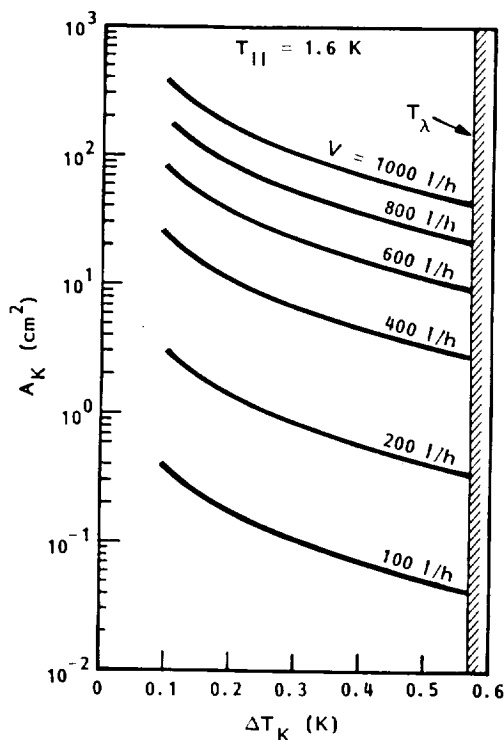


Fig. 3-37 Kapitza Heat Transfer Area Required for He-II at 1.6 K

where λ is the latent heat of vaporization. The heat capacitance of the dewar is neglected. As shown in Fig. 3-38, the volume fraction loss of evaporative cooling from 1.8 K to 1.6 K is only 1.7 percent.

Theoretically, the supply of energy to the Klipping-type FEP is zero. The standard thermodynamic efficiency is defined as the ratio of theoretical power consumption to the real power consumption. This yields a fictitious thermodynamic efficiency of infinity. The design of the porous plug is similar to that of the Leiden-type FEP, without the need of a heater downstream of the porous plug. However, auxiliary devices such as vent regulators and heater windings at strategic locations are needed to avoid overcooling of the supply tank during the cool-down phase of a hot receiver.

3.3.4 Pressurization

Pressurizing a supply tank to set up a pressure head is the most common technique used to transfer liquid between tanks. It is used routinely in both ground and on-orbit operations where high flow rates are not required. Some of the characteristics of the supply and receiver pressure profiles during the transfer are:

- Supply pressure
 - Constant
 - Blowdown
 - Blowdown with repressurization

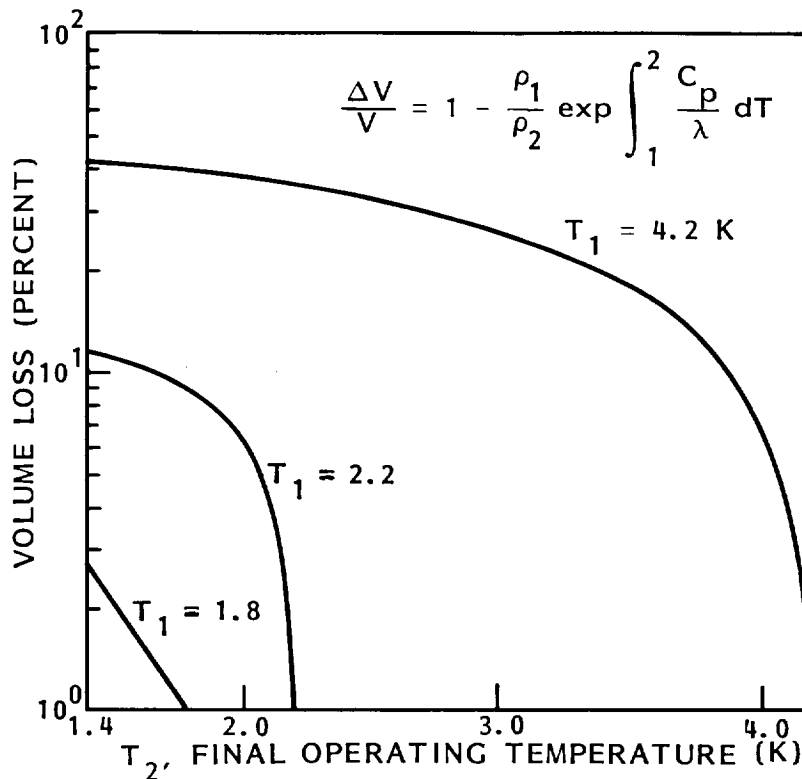


Fig. 3-38 Volume Fraction Loss in Evaporative Cooling from T_i to T_f

- Receiver pressure
 - Vented
 - Nonvented

For the case of a constant supply pressure a regulated gas supply is used. Generally this technique is used when a constant flow rate is required. The blowdown method is used when a high-pressure gas supply is opened to the supply tank to pressurize it. In this technique, as the tank is draining the ullage pressure drops. In some systems a number of gas supplies are used in parallel such that once the pressure and flow rate drops to a certain value, the supply tank is repressurized.

The pressurant gas should be one that is noncondensable with the cryogen being transferred. He gas is a good candidate for the transfer of LH_2 and normal LHe ($T > T_\lambda$). In the case of normal He the transfer should not be slow. If the transfer is too slow, pressurant gas may condense and add a substantial amount of energy to the liquid, especially if a warm pressurant gas supply is used. If He-II is transferred, the high conductivity of the liquid makes maintaining a positive pressure very difficult. Generally in these cases, LHe slightly above the lambda point is transferred and cooled to superfluid conditions by venting once in the receiver tank. Due to the losses in cooling the liquid, a subsequent topping off of the tank is required or a loss in lifetime of SIRTf will have to be accepted.

Another option is to pressurize the tank with helium-3 (He^3). At the desired temperature of 1.8 K the vapor pressure of He^3 is 102.5 torr, which is above the corresponding helium-4 (He^4) vapor pressure of 12.4 torr. This differential pressure of 90 torr can be used to transfer He-II. For the nominal 10,000-L supply volume, approximately 31.8 kg would be required to maintain a pressure of 100 torr during liquid transfer. In order not to add a tremendous amount of energy to the system, the He^3 gas must be supplied at no more than its critical temperature (3.2 K). If a lower final pressure would be sufficient, then the required amount of He^3 can be reduced.

It is possible that an instrument's open cycle cooler on the SIRTf may have to be replenished with 8.2 kg of He^3 . If this is the case, then the He^3 can subsequently be transferred to that cooler. The transferred He^3 will have He^4 vapor in it. The lower the final supply tank pressure is, the higher the concentration of He^4 will be. This concentration of He^4 may affect the operating temperature of the He^3 open-cycle cooler and needs to be studied. In addition, the He^4 transferred to SIRTf will have some dissolved concentration of He^3 . Its effect, if any, requires investigation.

The manner of liquid/vapor interface control would be the same as for the other transfer techniques, i.e., gallery systems. For the He system the cryogen must be transferred above the lambda point. This poses a difficult problem in the receiver tank in venting the normal He which makes a pressurized transfer technique unattractive. Utilizing He^3 as a pressurant gas may slightly change the lambda curve of liquid helium.

For transfer of LH_2 , pressurization with cold gaseous He appears attractive and is a well proven technique for propellant systems. A separate He container could be used at slightly elevated temperature, or the residual He in the He supply tank could be heated and used as a pressurant after filling the SIRTf He tank.

3.4 FLUID ACQUISITION AND MANAGEMENT

Design and development of systems for collecting and delivering liquid cryogens to the supply tank drain inlet presents unique problems in hydrodynamic and thermodynamic control. Solution of these problems requires perceptive interpretation of available technology and realistic appraisal of any need for new supporting technology. In general, the state of the art is sufficiently advanced at this time to warrant proceeding with designs to control liquid cryogens in low-g environments. There must be assurances that there are no failure modes that cannot be accommodated by design schemes. Analyses are necessary to determine the draining efficiency of these devices because low residuals in the supply tank are essential. Three types of fluid control have been demonstrated successfully in flight. They are:

- (1) Settling accelerations
- (2) Passive expulsion (surface tension devices)
- (3) Positive expulsion

Each of these offers unique advantages and disadvantages when applied to a set of requirements.

3.4.1 Requirements

The cryogen transfer requirements for SIRTf are based primarily on the need to transfer He-II and LH₂. Table 3-7 shows the requirements that were established for review and preliminary design of the low-g cryogen control systems for SIRTf. For the He system, the on-orbit vent of the supply tank with He-II is essentially performed by the porous plug. This simplifies the design, since there is no need to control the vapor ullage around the vent line. In the case where normal He or LH₂ is the supply cryogen, the system must control both the vapor and liquid. These systems must be compatible with both shuttle or space station operation. Preliminary estimates of the drag forces on the space station are approximately 10^{-5} to 10^{-4} g_0 oriented in a favorable direction. This means that the acceleration vector will be in a constant and predictable direction. This acceleration is primarily due to the drag forces and must be overcome periodically to readjust the space station from its orbit decay. Different options are available. The two best candidates are to perform orbit adjusts three or four times per orbit or once when the orbit has decayed to 350 km from its nominal 500-km altitude. In either case, during the orbit adjust the acceleration field is expected to be approximately 10^{-3} g_0 . Depending on the system that will perform the fluid acquisition, it may not be desirable to transfer during these periods. Various estimates and measurements of the drag forces on the shuttle have been made. The drag forces are sensitive to altitude and shuttle orientation with respect to the shuttle orbit velocity vector. A reasonable range was found to be 10^{-4} g_0 to 10^{-8} g_0 , which is expected to occur in any adverse direction. Based on the cryogen requirements established by the thermal

Table 3-7 FLUID MANAGEMENT DEVICE REQUIREMENTS

- Helium System
 - Wet or dry receiver tank resupply
 - Vapor vent of receiver tank
 - Superfluid liquid transfer to receiver tank
 - Shuttle or space station operation
 - Option 1
 - Ground fill of supply tank with normal boiling point helium
 - On-orbit vapor vent to cool helium to superfluid conditions
 - Option 2
 - Ground fill of supply tank with superfluid helium
- Hydrogen system
 - Ground fill of supply tank with liquid hydrogen (slush also option)
 - On-orbit vapor vent of supply tank
 - Wet or dry receiver tank resupply
 - On-orbit vapor vent of receiver tank
 - Liquid transfer to receiver tank (slush also option)
 - Shuttle or space station operation

cool-down and fill analysis, the supply volumes are 10,000 L for He and 2,800 L for LH₂. Figures 3-39 and 3-40 show schematics of the tanks that are used in the following analysis.

3.4.2 Settling Accelerations

Induced accelerations can be used for orienting liquid/vapor interfaces in a known location for effective draining of cryogenics from the supply tank. The major concern in low-g draining is the prediction of liquid residuals that remain after vapor ingestion into the transfer line. The governing similarity parameters are the Bond, Weber, or Froude number defined as follows:

$$\begin{aligned} \text{Bond No. (B)} & \quad \rho g a^2 / \sigma \quad (\text{ratio of body to surface forces}) \\ \text{Weber No. (W)} & \quad \rho Q^2 / \sigma a^3 \quad (\text{ratio of draining to surface forces}) \\ \text{Froude No. (F)} & \quad Q^2 / g a^5 \quad (\text{ratio of draining to body forces}) \end{aligned}$$

In these expressions, Q = volumetric drain rate, g = acceleration, σ = surface tension, a = tank radius, and ρ = liquid density; also, $F = W/B$. Figure 3-41 shows the kinematic surface tension of the three cryogenics of interest as function of temperature and in relationship to three conventional storable propellants for which surface tension devices are routinely designed. The propellants are nitrogen tetroxide (N₂O₄), monomethyl hydrazine (MMH), and anhydrous hydrazine (N₂H₄). The kinematic surface tension of H₂ lies in the realm of conventional propellants, but that property in He is significantly lower than N₂O₄, the propellant with the lowest surface tension value.

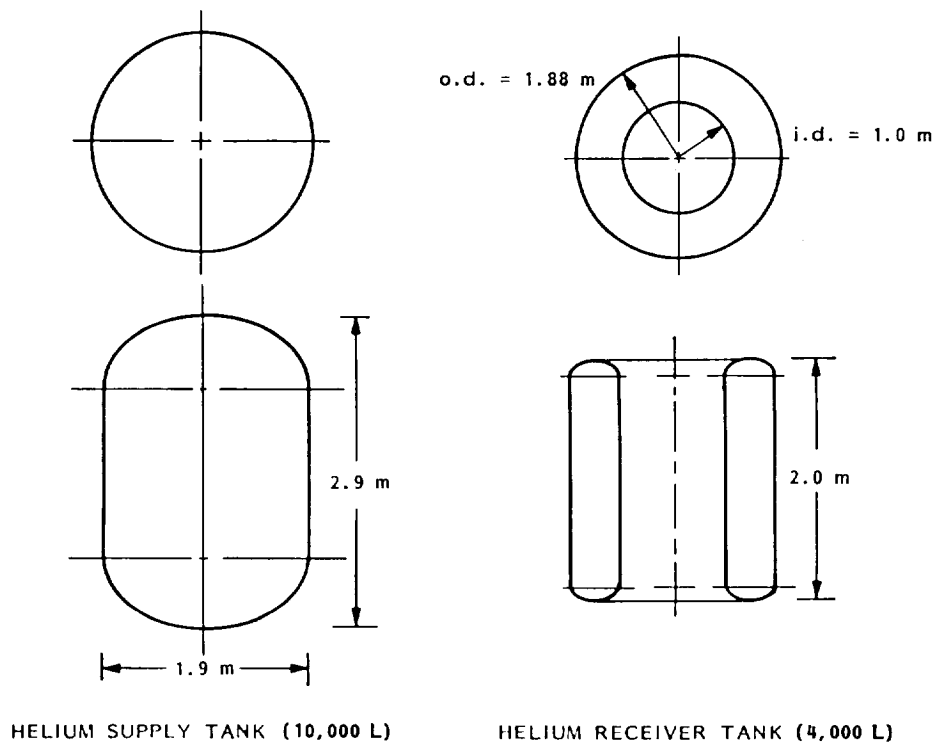
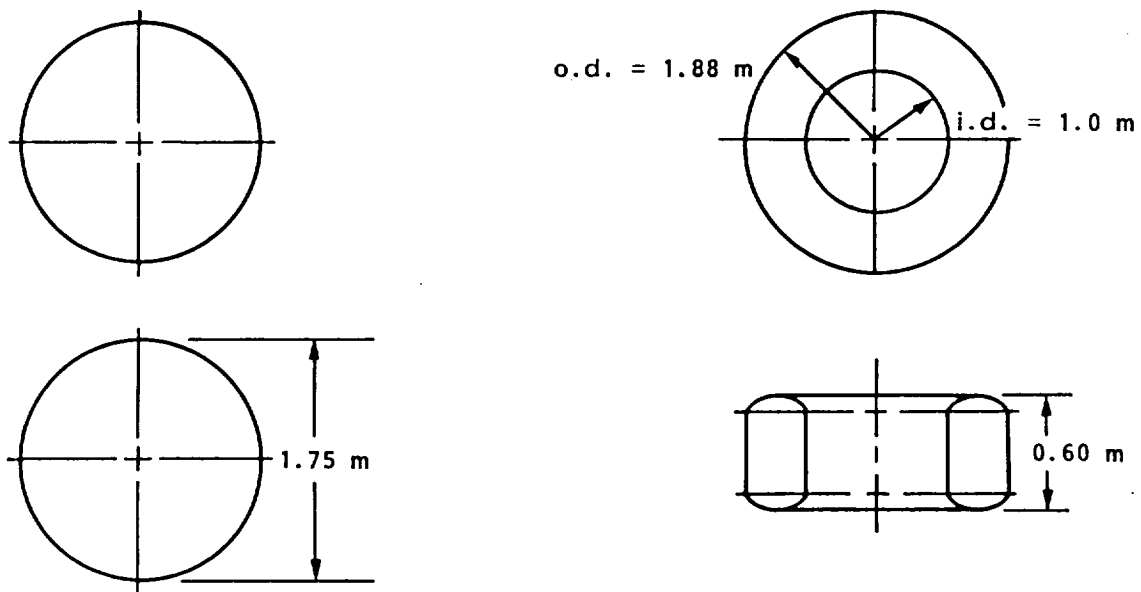


Fig. 3-39 He Tankage



HYDROGEN SUPPLY TANK (2,800 L)

HYDROGEN RECEIVER TANK (1,650 L)

Fig. 3-40 H₂ Tankage

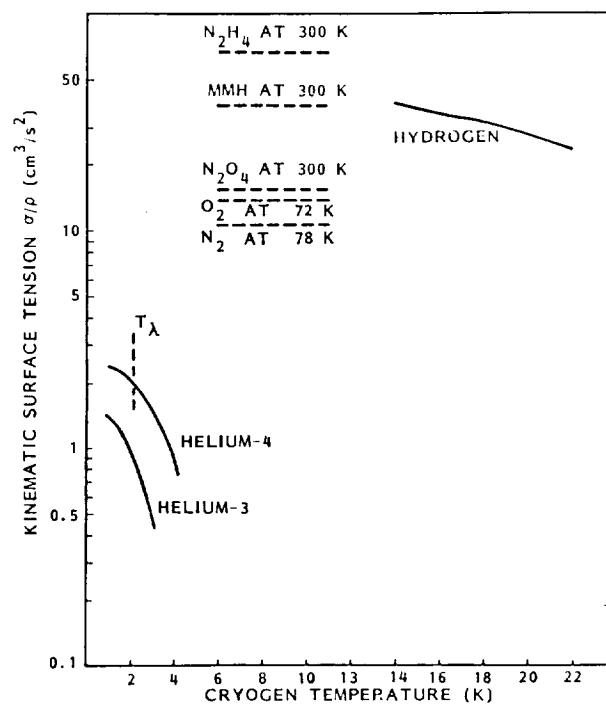


Fig. 3-41 Cryogen Kinematic Surface Tension

To design a system which uses acceleration to control the liquid/vapor interface in the tanks, the bond number must be large enough. Figure 3-42 gives typical bond numbers for He-II and LH₂ for tanks small enough to fit in the cargo bay of the shuttle. These data show the importance of accelerations greater than $10^{-5} g_0$ for LH₂ such that body forces dominate surface tension forces ($B > 1$). Due to the lower surface tension of He-II, the required acceleration is much lower. Since the liquid/vapor interface is known under these accelerations, ventability of these tanks can be assured.

Four possible system orientations associated with a transfer from the space shuttle that employ induced accelerations are shown in Fig. 3-43. Selection of one over any other will depend upon the vehicle characteristics and operational impact. As discussed previously, the on-orbit transfer between supply and SIRTf tanks may take as long as several days for an efficient cool-down and fill of a warm telescope and dewar. It may be undesirable or unfeasible to apply these body forces for this duration. Linear acceleration is a typical method used with propellants to orient liquids over the tank outlet.

In the case of a transfer from the shuttle or space station, the weights are much larger than that of this payload. Thus, to transfer by linear acceleration would require great amounts of propellants. It may be more feasible to induce a roll rate to orient the liquids. For a desired acceleration of $10^{-5} g_0$, a rate of less than 0.1 rpm would be sufficient for tanks up to 200 cm in radius.

Another technique to induce accelerations is to have the SIRTf and supply facility connected to and revolve about the shuttle or space station. This tethered system is presently being considered for transfer of propellants. These methods of applying accelerations are not particularly attractive due to:

- (a) Extremely active system
- (b) Complicated controls
- (c) Vehicle motion complications

The last method is to orient the tanks such that the drag accelerations settle the cryogen over the tank outlets. On the shuttle this may not be possible because:

- (a) The shuttle flies with various planes of the vehicle forward
- (b) RCS thrusting would interfere with the drag induced liquid settling
- (c) Crew activity may dominate shuttle recorded accelerations

On the space station where drag forces are in a constant direction and where crew activity effects on the station acceleration are small, it may be possible to correctly orient the tanks. In this case the liquid would settle over the tank outlet and gas/vapor would occupy the region around the vent tube.

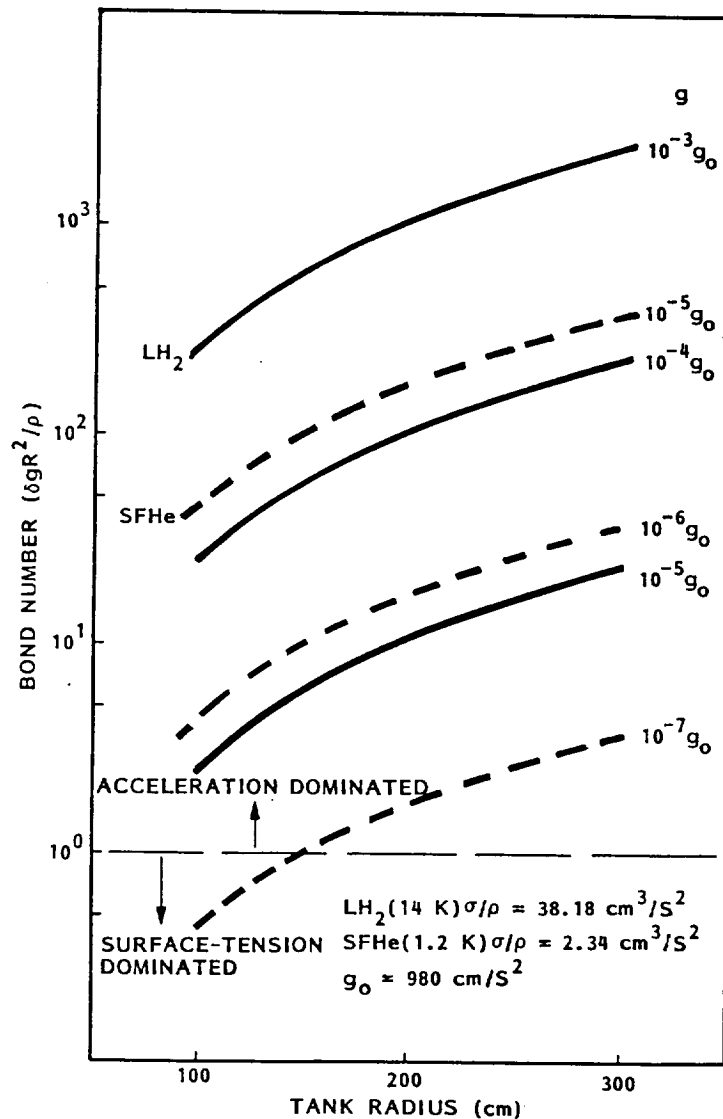


Fig. 3-42 Typical Tank Bond Numbers of Cryogenics in Tanks

Since the forces on the liquid due to accelerations are small, the dynamic effects of removing liquid from a tank may create surface dip and vortex which can lead to high residuals once vapor is ingested into the outlet. Many analyses and tests have been conducted to predict vapor ingestion height in hemispherically bottomed tanks with no internal hardware near the drain inlet or with baffles. Once nominal choices of optimum values of flow rate and drain times are established, further attention can be paid to engineering design to eliminate residuals. It can be argued that the use of sufficient baffling can eliminate nearly all residuals. Typical designs used presently in propulsion applications are sponge devices with velocity control screens.

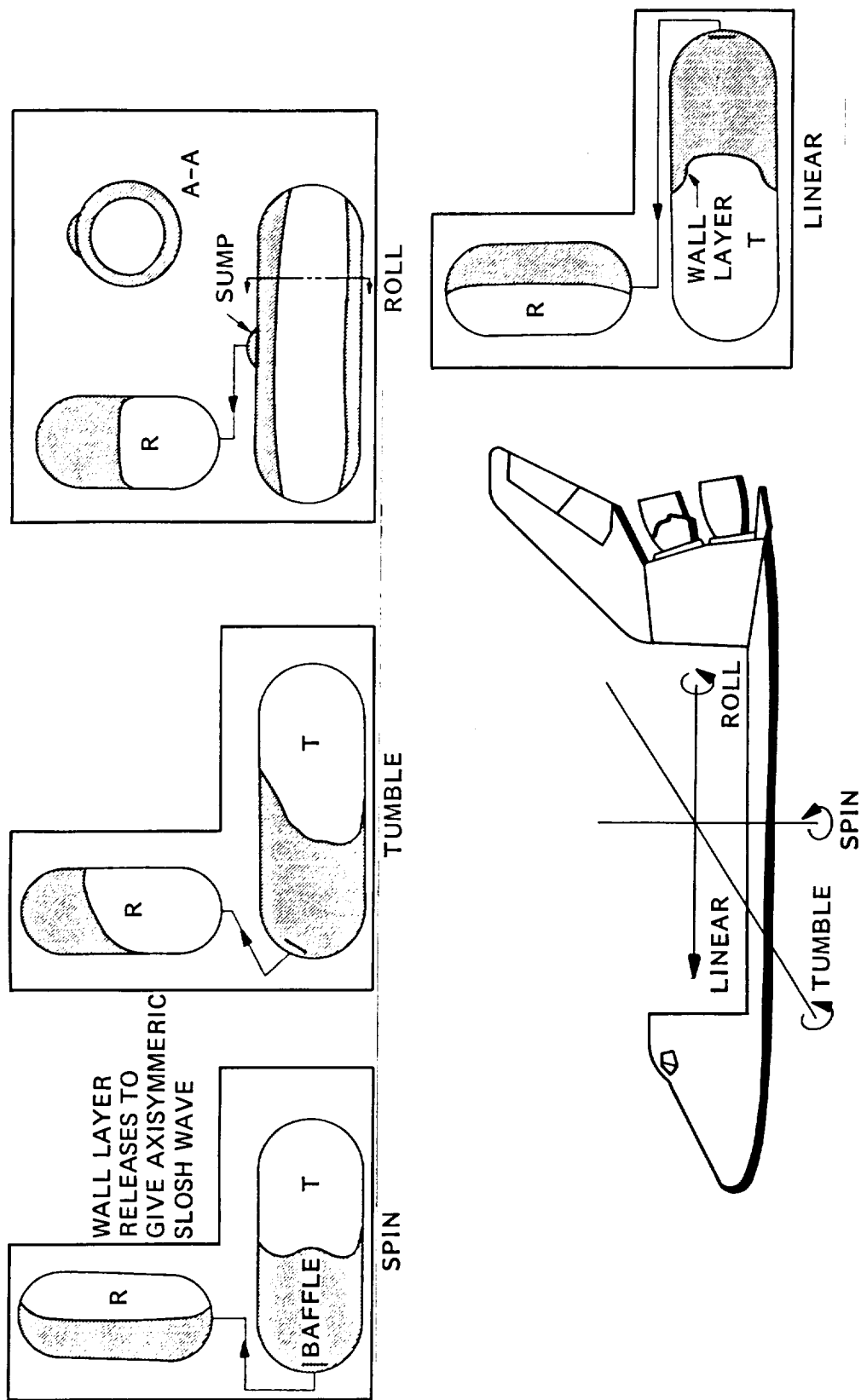


Fig. 3-43 Acceleration Transfer Concepts Using Earth-to-Orbit Shuttle as Launch Vehicle

3.4.3 Surface Tension Devices

Surface tension devices are divided into the broad categories of open capillary passages, enclosed capillary passages, and a mixture of the two. The open devices potentially have less problems with gas entrainment but do not possess the high capillary stability against disturbing forces. These devices are completely passive. Their integrity can be compromised if they are not kept free of gas. This implies a necessary compatibility with the thermal control, pressure control, and pressurization systems (as required). Integration of a tank vent system and the surface tension device must take into consideration all probable operating modes; the independent conditions and requirements for proper functioning of each system; and finally various ways in which the proper operation of one system will adversely affect operation of the other. If these problems are solved, analyses are still necessary to determine overall efficiency of these devices, because low residuals in the supply dewar are desirable.

To design screen liners and galleries and to determine hardware weight and the weight of residuals, it is necessary to offset the pressure drops of the acquisition system with sufficient capillary head across the screens to prevent bubble breakthrough. This is expressed by:

$$\Delta P_{CAP} \geq \Delta P_{ENTRANCE} + \Delta P_{LINE \text{ FRICTION}} + \Delta P_{DYNAMIC} + \Delta P_{HYDROSTATIC}$$

$$\Phi \frac{\sigma}{r} \geq C_D \frac{\rho Q^2}{2g_c A_s^2} + \frac{\rho f}{2g_c d} \int_0^L \frac{Q^2}{A_e^2} dL + \frac{\rho Q^2}{2g_c A_e^2} + \frac{\rho gh}{g_c}$$

where

- A_s = submerged area (puddle)
- A_e = entrance to baffle/drain chamber over drain
- C_D = drag coefficient for flow through screen surface
- d = flow channel hydraulic diameter
- f = friction factor
- g = local acceleration
- g_c = units conversion factor
- h = cross length measured parallel to acceleration vector
- L = flow length
- Q = volumetric flow rate
- r = effective hole radius for retention screen
- ρ = propellant density
- σ = propellant surface tension
- Φ = dimensionless parameter ($\rho g r h / \sigma$) for measured capillary support limits

After examining the different devices including vanes, galleries, baffles, troughs, traps, and sponges, a concept matrix was generated for the various

requirements. This matrix shown in Table 3-8 indicates the most likely concept to be utilized successfully in this application. Where two options are given the first will work under all the expected operating conditions and the second option shall be considered but warrants some development work. In the receiver tanks which require high ventability, baffles or metallic foam were considered.

3.4.3.1 Gallery Devices. The gallery arm concept is illustrated in Fig. 3-44. A gallery arm tank consists of four or more screen covered channels which traverse the tank close to the tank wall. The device prevents gas from leaving the tank by utilizing surface tension forces in the wet screen. Liquid can flow through the screen with relatively low losses while gas has to overcome the surface tension forces of the liquid in between the wires in the screen. Once within the gallery arm liquid flows down the gallery arm and out the outlet.

Table 3-8 LIQUID MANAGEMENT DEVICE CONCEPT MATRIX

Mission Requirement	Cryogen	Supply Tank		Receiver Tank
		Liquid Drain	Vapor Vent	Vapor Vent Only
Space Shuttle Adverse Accelerations 10 ⁻⁴ to 10 ⁻⁸ g's	He-II	Gallery	Porous plug	Porous plug
	NBPHe	Gallery		Not required
	LH ₂	Gallery or baffle	Baffle ¹	Baffle ¹ or foam
Space Station Favorable Accelerations 10 ⁻⁴ to 10 ⁻⁵ g's	He-II	Baffle or Sponge	Porous plug	Porous plug
	NPBHe	Baffle or sponge	Ventable by favorable acceleration only	Not required
	LH ₂	Baffle or sponge acceleration only ²	Ventable by favorable	Baffle or foam

¹Baffle permits venting capability only to adverse accelerations up to 1 x 10⁻⁵ g's

²A sponge may be desirable over drain for intermittent adverse accelerations.

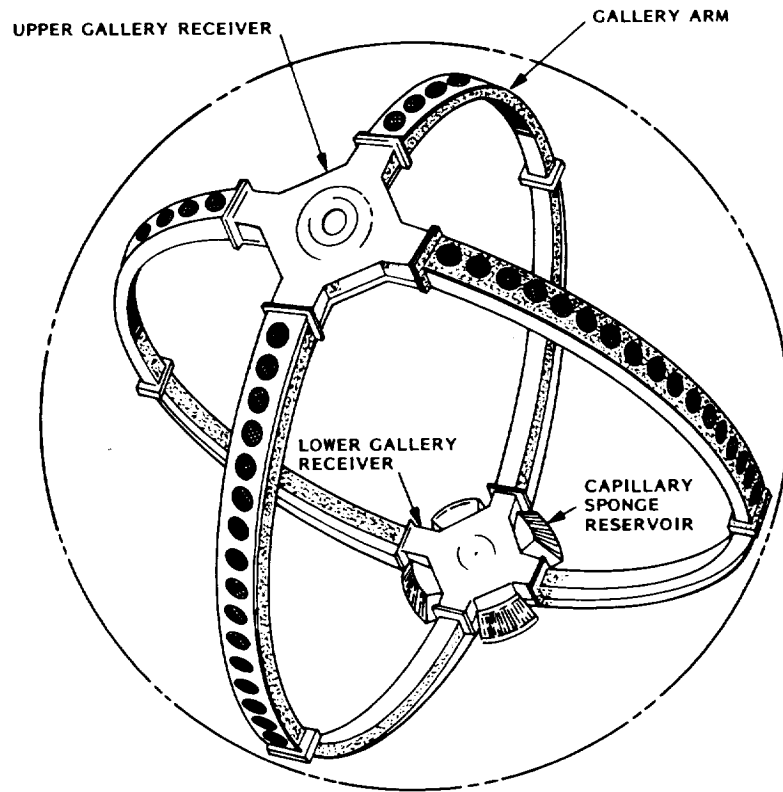


Fig. 3-44 Fluid Management Devices Gallery Concept for Liquid Draining (Supply Tank)

The gallery device allows liquid to move about in the tank and ensures access by positioning gallery arms symetrically around the tank. Because the liquid is free to move about the tank, it is impossible to position a vent tube such that it is only in the vapor ullage during all accelerations the tank might experience. The characteristics of the gallery device are:

- (a) Communication device (no liquid control)
- (b) Omnidirectional accelerations
- (c) Relatively high accelerations
- (d) Moderate flow rates
- (e) Moderate residuals
- (f) Nonventable

The capabilities of the gallery arm tank depends upon the size of the tank, the fluid used, and the equivalent hole size of the porous element used (i.e., the screen). The capabilities are defined by:

- (a) Maximum operable acceleration
- (b) Maximum operable flowrate
- (c) Nominal residual liquid

For a given fluid and given tank size the porous element can be sized to accommodate a range of accelerations. To illustrate the gallery arms

capabilities, an equivalent hole size of 93 μm was used. Porous elements are available down to 10 μm , but flow losses increase dramatically and maximum flow rates will decrease. The capabilities in Table 3-9 assume one pore size. If higher accelerations and lower flow rates are required, a smaller hole size can be chosen. The ability of the gallery arm tank to adapt to a variety of requirements makes its use attractive and widespread in propulsion systems.

3.4.3.2 Baffle Devices. A baffle concept is illustrated in Fig. 3-45. This concept is a design for a 36-in. diameter cylindrical tank for the Viking orbiter. The baffle system uses surface forces to hold the liquid in the baffle and away from the vent tube. Because the spacings between the baffle are larger than the holes in screen, and the surface tension forces are inversely proportional to the hole or slot size, the capabilities of the baffle device are lower than that of the gallery device.

The advantages of the baffle device are in its characteristics. First, this device is ventable under limited accelerations. It can operate effectively under high settling accelerations. It offers slosh control, and the residual propellant left behind in a baffle tank is often less than 0.1 percent of the tank volume.

Figure 3-46 is a pictorial view of liquid in a baffle device tank. The figure shows that during lateral, rearward, and forward accelerations the ullage gas remains over the end of the vent tube, thus allowing ventability. The baffle is shaped such that a taper exists between the tank wall and the baffle, thus forcing the gas toward the vent tube.

Table 3-9 GALLERY ARM DEVICE CAPABILITIES*

● He Supply (~10,000 L)		
- Maximum adverse operating acceleration		$2 \times 10^{-4}g$
- Maximum allowable flow rate		$\sim 20 \text{ in.}^3/\text{s}$ (1,180 L/h)
- Nominal residual		<1 percent V_T
- Device mass		30-60 lbm
● H ₂ Supply (~2,800 L)		
- Maximum operating acceleration		$9.9 \times 10^{-3}g$
- Maximum allowable flow rate		$\sim 40 \text{ in.}^3/\text{s}$ (2,360 L/h)
- Nominal residual		<1 percent V_T
- Device mass		20-40 lbm

*Based on currently available titanium porous materials.

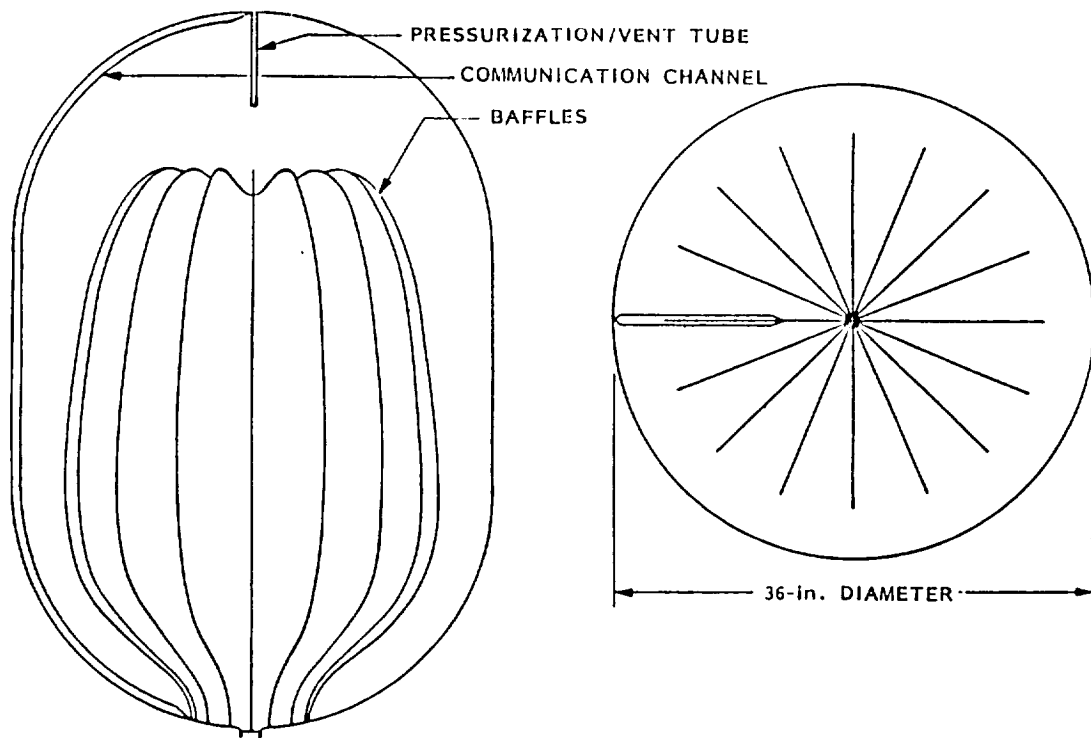


Fig. 3-45 Viking Propellant Acquisition System

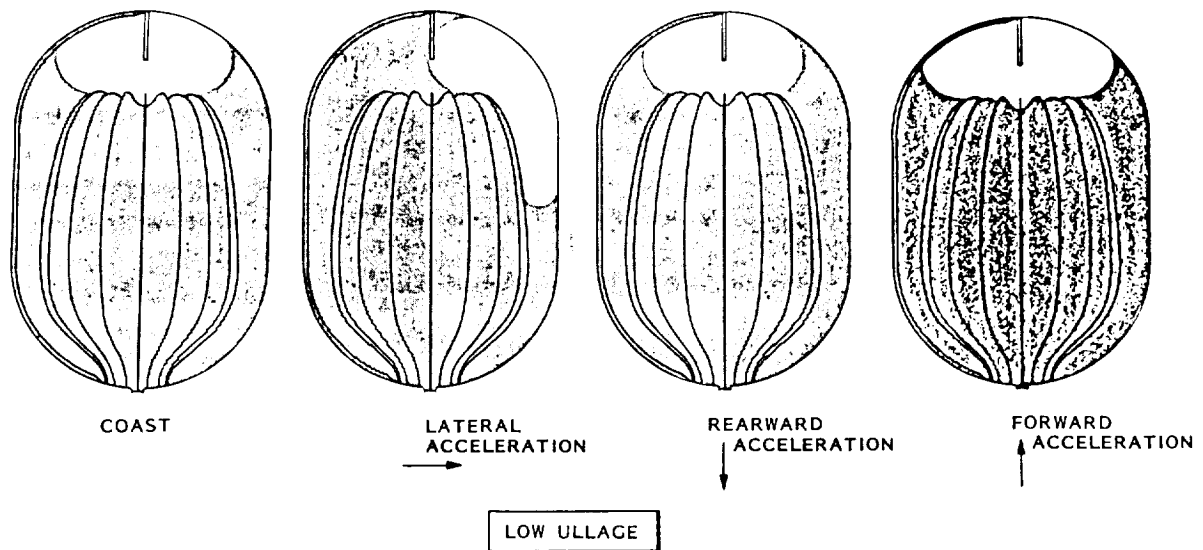


Fig. 3-46 Fluid Management Devices Baffle Concept - Operation

The capabilities of this device can be characterized as a function of tank size and shape, fluid, and number of baffles. By increasing the number of baffles, the distance between baffles decreases and the surface tension forces increase, thus giving the tank more capability in terms of acceleration and flow rate. Tables 3-10 and 3-11 show the capabilities of different devices with different applications.

Table 3-10 shows the capabilities of a device shape designed to allow ventability with the tank up to 95 percent filled. The table addresses 16 and 32 baffle designs in both the helium and hydrogen supply tanks. Table 3-11 shows the capabilities of a device for venting with no accommodation for liquid draining in orbit.

The baffle concept appears attractive for applications where the accelerations are small. With large adverse accelerations as encountered during shuttle reaction control subsystem (RCS) primary thrust, the device may not be suitable. However, the device will function properly if the primary thrust is pulsed and not fired continuously. The exact shuttle mission profile should be examined to determine suitability of the baffle concept. If it can be accommodated, it represents one effective method for liquid control in low g.

3.4.3.3 Sponge Devices. The sponge concept is similar to the baffle concept. A sponge is generally smaller and capable of higher accelerations, but it is only ventable during settling accelerations. This is because it

Table 3-10 FLUID MANAGEMENT DEVICES BAFFLE CONCEPT - SUPPLY TANKS

CONCEPT CAPABILITY	VIKING ORBITER 16 BAFFLE	HELIUM SUPPLY 16 BAFFLE	HYDROGEN SUPPLY 16 BAFFLE	HELIUM SUPPLY 32 BAFFLE	HYDROGEN SUPPLY 32 BAFFLE
MINIMUM VENTABLE ULLAGE	<5%	<5%	<5%	<5%	<5%
MAXIMUM ADVERSE ACCELERATION	$1.5 \times 10^{-5} \text{ g}$	$1.4 \times 10^{-7} \text{ g}$	$5.3 \times 10^{-6} \text{ g}$	$3.0 \times 10^{-7} \text{ g}$	$1.0 \times 10^{-5} \text{ g}$
MAXIMUM FLOWRATE	20 in. ³ /s (1180 l/h)	12 in. ³ /s (708 l/h)	57 in. ³ /s (3,363 l/h)	16 in. ³ /s (944 l/h)	80 in. ³ /s (4,720 l/h)
NOMINAL RESIDUAL	0.1% V_T	0.1% V_T	0.1% V_T	0.1% V_T	0.1% V_T
MANAGEMENT DEVICE MASS	15 lbm	40-80 lbm	30-70 lbm	80-160 lbm	60-140 lbm

Table 3-11 FLUID MANAGEMENT DEVICES BAFFLE CONCEPT FOR VENTING ONLY - RECEIVER TANK

CONCEPT CAPABILITY	VIKING ORBITER 16 BAFFLE	HELIUM RECEIVER 16 BAFFLE	HYDROGEN RECEIVER 16 BAFFLE	HELIUM RECEIVER 48 BAFFLE	HYDROGEN RECEIVER 48 BAFFLE
MINIMUM VENTABLE ULLAGE	<5%	<50%	<50%	<10%	<10%
MAXIMUM ADVERSE ACCELERATION	$1.5 \times 10^{-5} \text{ g}$	$2 \times 10^{-7} \text{ g}$	$7 \times 10^{-6} \text{ g}$	$5 \times 10^{-7} \text{ g}$	$2 \times 10^{-5} \text{ g}$
MANAGEMENT DEVICE MASS	15 lbm	15-25 lbm	5-15 lbm	125-175 lbm	50-75 lbm

retains only a portion of the tank's liquid over the outlet for use. The majority of the tank liquid is free to move about the tank during the accelerations encountered. A schematic isometric of a sponge is shown in Fig. 3-47.

The sponge is:

- A partial control device
- Refillable
- A buffer for short-duration flow and acceleration transients
- Operable during settling accelerations
- Ventable during settling accelerations

A sponge can be sized to accommodate liquid flow out of the tank during the time required to reorient the liquid over the outlet during a settling acceleration. The sponge can therefore be sized to accommodate venting and outflow during any settling acceleration. Sponges have been used successfully in many propulsion systems.

3.4.3.4 Foam Device. When metal is sintered to form foam, the passages formed between the metal can be filled with liquid. Again, due to surface tension, the liquid will be controlled during adverse accelerations. Although foam functions as a baffle device, the size of the pores may be reduced

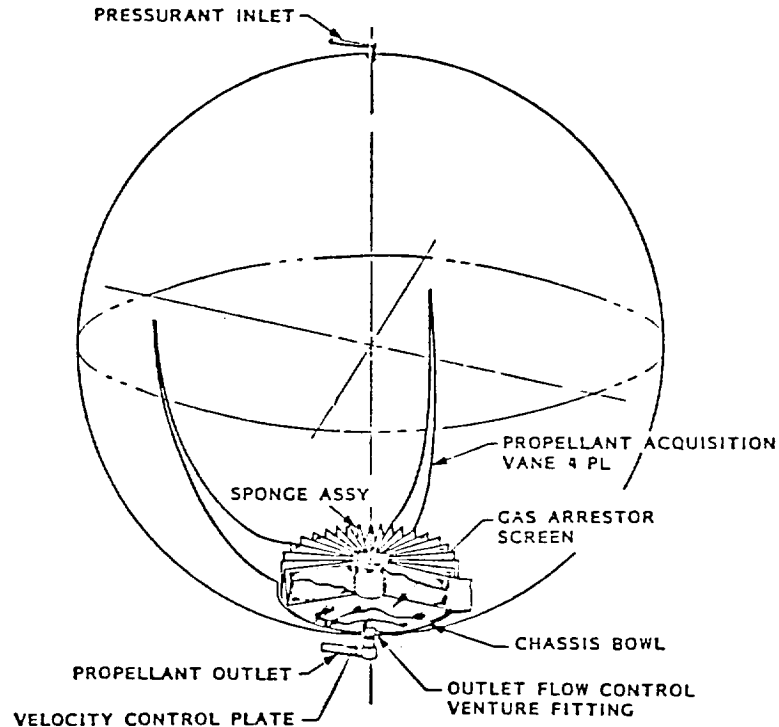


Fig. 3-47 Fluid Management Devices Sponge Concept

dramatically, and thus the capability of foam to resist fluid motion is great compared to a baffle device. The characteristics of a foam device include:

- Variable density
- Thermally conductive
- Nonuniformity to some extent

The capabilities are the same as a baffle device, except that foam will retain liquid and allow ventability at higher accelerations, perhaps 100 times higher.

The disadvantages are that foam is not as predictable in pore shape as baffles or other porous media and therefore may require testing prior to use in SIRTf. Because of the nonuniformity and unpredictability it is difficult to analyze without some testing the effect of filling on orbit. The prospect of it being able to meet mission requirements makes it a candidate for a liquid management device. Development testing is recommended.

3.4.3.5 Conclusions. Passive devices can be designed to meet a number of requirements for the low-g management of cryogenics for the SIRTf resupply tank. Their performance can be limited by the acceleration they are subjected to. If the acceleration is in a favorable direction and high enough to settle the cryogen over the tank outlet of the supply tank, passive devices can be used to ensure a high depletion level. When the acceleration is unfavorable, the requirements on the devices are greatly increased. The gallery device will ensure liquid communication to the supply tank outlet for both H₂ and

He. However, this device will not control the location of the vapor ullage for venting purpose. During short periods of high accelerations that may overcome the gallery device, a sponge can be a buffer such that the flow will not be interrupted.

If the accelerations are low enough, a baffle device can be used in the supply or receiver tanks and control the vapor for ventability. The device with the highest prospects to meet the requirements for the receiver tanks is metallic foam. This device can withstand high accelerations while the tank is being vented. The major disadvantage of the foam is that its ability to fill without trapping pockets of vapor is presently unknown and needs investigation. The surface tension device selection is extensive, and, given the mission, one or more shall be applicable.

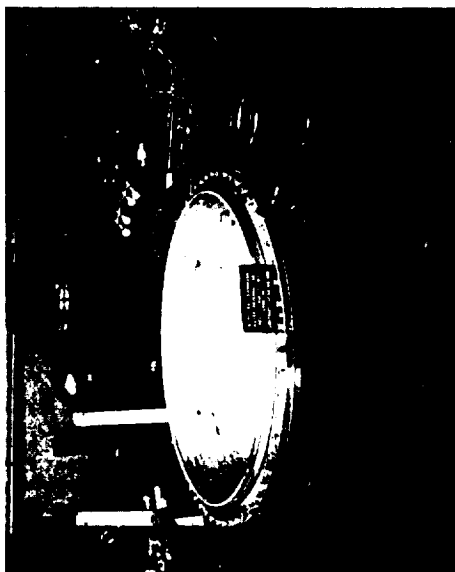
3.4.4 Positive Expulsion Devices

Expulsion bladders which are driven by pressurant gas effectively provide separation between the ullage vapor and liquid. They permit liquid expulsion in a low-g environment without the need for other fluid control devices. Implementation of this device into a cryogenic system may restrict the use of internal components such as liquid-level sensors and venting devices for controlling the pressure in the liquid space (if required). They are also somewhat limited by geometry constraints.

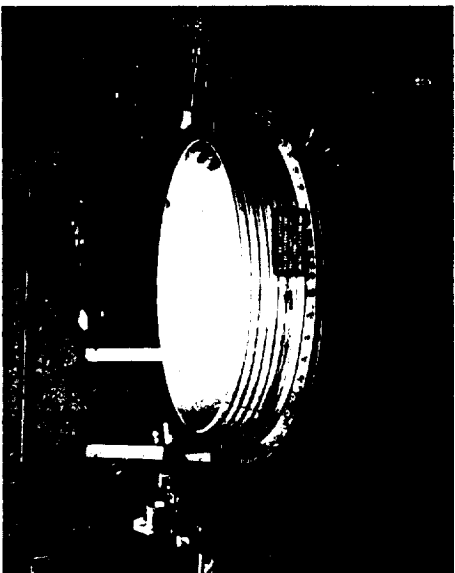
Some research and development work has indicated that polymeric cryogenic expulsion bladders may be feasible with LH₂ (Ref. 39). Materials have been tested to determine if they are compatible with the low temperatures. A number of studies were directed to understanding and confirming permeability and flexibility. It was found that multiple bladders are necessary for reliability, flexibility, and permeability for storing and expelling cryogenic liquids. Fabrication and installation techniques of the individual plies have been examined to best eliminate any problems. However, they have not been adequately developed at this time to provide a confident approach for tank expulsion.

Another bladder design that has been used extensively with storable propellant tanks has great potential with cryogenics. This tank (Fig. 3-48) is also a positive expulsion device but uses a metallic diaphragm to separate the liquid and the pressurant gas. The diaphragm, which attaches to the tank at the equator, is a formed sheet 0.014 in. thick made of type 304L corrosion resistant steel (CRES) stiffened on the pressurant side by type 308 CRES rings. Tanks of various sizes up to 72 in. in diameter (Fig. 3-49) have been flight qualified and flown successfully or demonstrated with this type of metallic diaphragm.

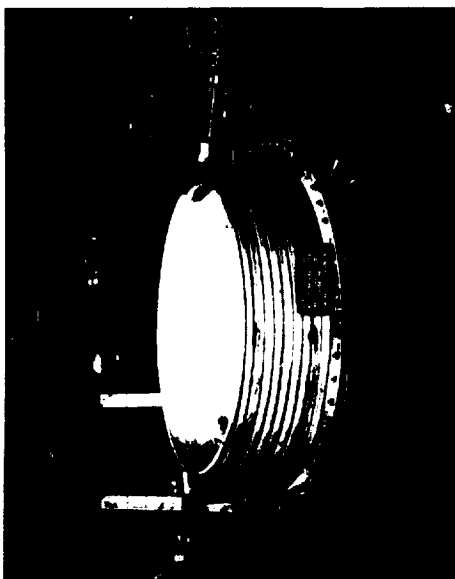
Use of a metallic bladder for He-II may present difficulties in maintaining the pressurant gas due to heat transfer across the metallic bladder in the extremely high thermally conductive He-II. This may require insulation of the bladder to maintain sufficient pressure of the pressurant gas.



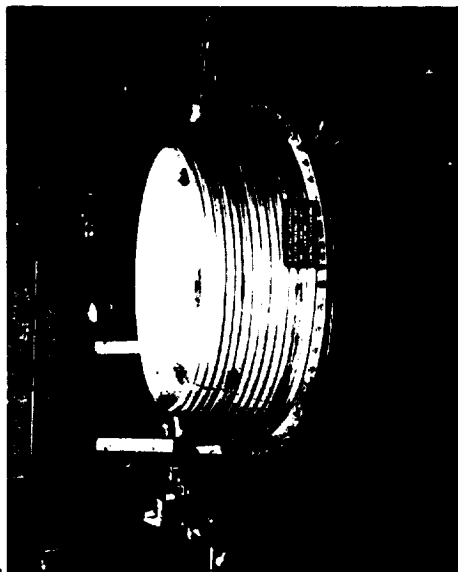
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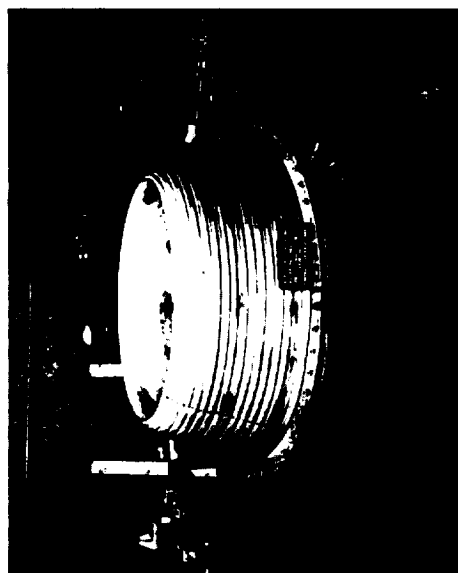
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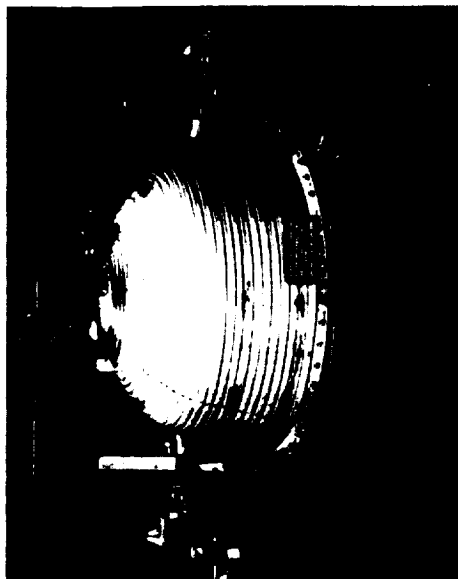
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6

Fig. 3-48 72-in. diameter Ring Reinforced Diaphragm Reversal Test

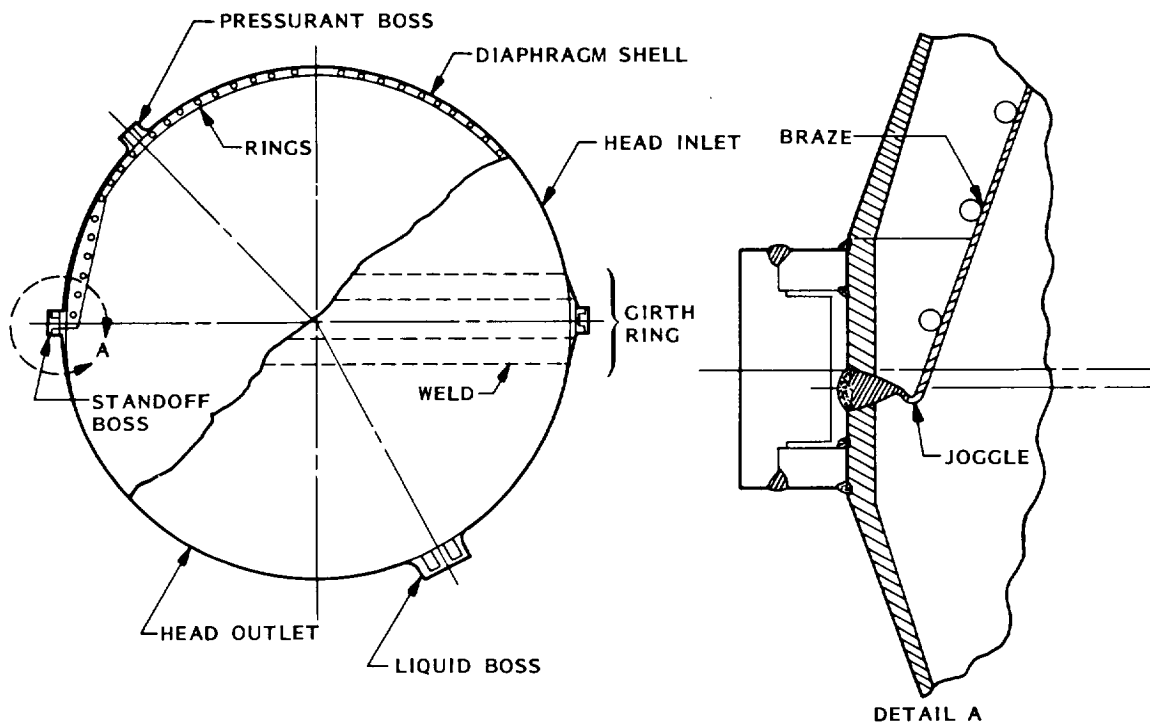


Fig. 3-49 Positive Expulsion Tank Using a Metallic Diaphragm

3.4.5 Mass Flow Gaging Techniques

Following cryogen replenishment (and throughout the mission) it is important to know as accurately as possible the total mass of cryogen that has been transferred to and is remaining in the SIRTF tank(s). This will allow continual updating of the projected cryogen lifetime so that scientific experiments can be planned and replenishment missions scheduled.

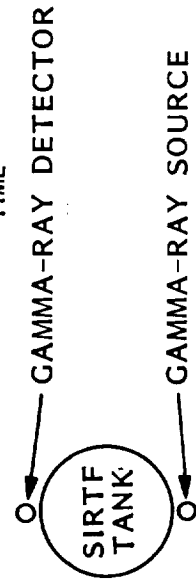
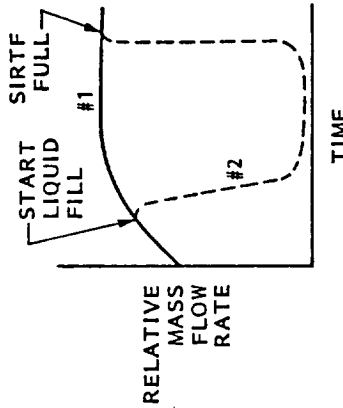
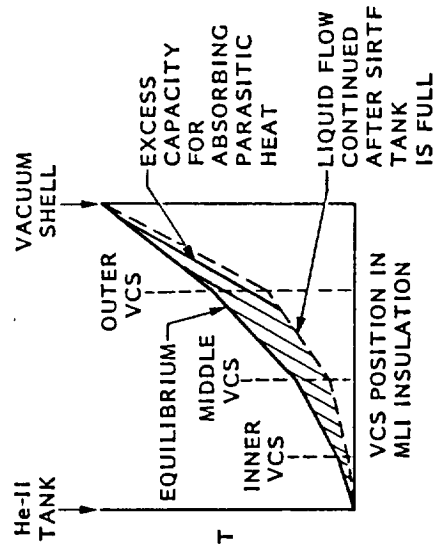
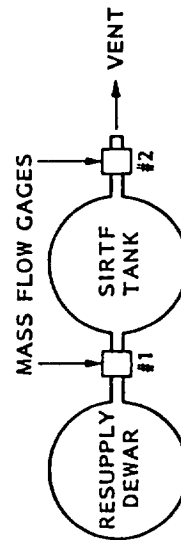
Several gaging techniques are possible for on-orbit replenishment as shown in Fig. 3-50. This mass balance technique is a modified version of a proven ground loading method. Two mass flow gages are required to measure the He vented from both the supply and SIRTF tanks in addition to ground-based weighings. Four measurements are required (with varying degrees of accuracy) which affect the overall measurement accuracy. This technique would apply for a direct shuttle resupply mission.

Another measurement, equal mass flow rates, can supplement the mass balance method and is also shown in Fig. 3-50. Mass flow measurements on both the supply tank outlet and SIRTF vent allows verification of a full tank when the flow rates are equal indicating liquid breakthrough in the SIRTF porous plug. Flow would be continued past this point to purposely depress the temperatures in the vapor-cooled shields, so excess capacity is available in the MLI and shields to absorb parasitic heat after the supply dewar is disconnected. Problems of restarting the porous plug as a phase separator after fill need to be examined.

- MASS BALANCE (REQUIRES TWO MASS FLOW GAGES PLUS A WEIGHING SCALE)

$$\begin{array}{rcl}
 \text{MASS LOADED} & = & \text{NET SUPPLY} \\
 \text{IN SIRTf TANK} & & \text{DEWAR WEIGHT} \\
 & & \text{(GROUND MEASUREMENT)} \\
 & - & \text{SUPPLY DEWAR} \\
 & & \text{VENT LOSS} \\
 & & \text{DURING LAUNCH/} \\
 & & \text{REENTRY PHASES} \\
 & & \text{(MASS FLOW} \\
 & & \text{GAGE ON} \\
 & & \text{SUPPLY DEWAR} \\
 & & \text{VENT LINE)} \\
 & - & \text{SIRTf} \\
 & & \text{DEWAR} \\
 & & \text{VENT LOSS} \\
 & & \text{DURING} \\
 & & \text{FILL} \\
 & & \text{(MASS FLOW} \\
 & & \text{GAGE ON} \\
 & & \text{SIRTf} \\
 & & \text{VENT LINE)} \\
 & - & \text{NET} \\
 & & \text{SUPPLY} \\
 & & \text{DEWAR} \\
 & & \text{WEIGHT} \\
 & & \text{FOLLOWING} \\
 & & \text{LANDING} \\
 & & \text{(GROUND} \\
 & & \text{MEASURE-} \\
 & & \text{MENT)}
 \end{array}$$

- EQUAL MASS FLOW RATES (REQUIRES 2 MASS FLOW GAGES)



- RADIOACTIVE GAGING

Fig. 3-50 Cryogen Mass Gaging Techniques

If both the mass balance and equal mass flow rate methods are used to complement each other, two mass flow gages are required on the supply tank and one mass flow gage on the SIRTF vent line.

A candidate liquid mass flow gage is the ultrasonic type. A candidate gas mass flow gage is the specific heat type. The ultrasonic gage has been used with LO_2 and LN_2 ; the manufacturer feels that the gage would also work with He or LN_2 . The sensor is rugged and heat dissipation is low, but the electronics would have to be repackaged for a flight application. The specific heat gage was flown successfully on IRAS.

Another method for mass gaging to be considered is the radiation absorption gage. A radioactive source, i.e., Krypton 85 emitting 0.15-MeV gamma rays, and suitable solid-state detectors are located on opposite sides of the tank(s). This method measures total mass (liquid and vapor) and is not affected by temperature or state changes.

A classified program used this technique to monitor hydrazine quantity. The accuracy of the system was marginal; however, use of new solid-state detectors in place of Geiger-Mueller tubes should improve the accuracy considerably. To achieve maximum accuracy, this system needs to be calibrated in place and used outside areas of high Van Allen radiation. This measurement technique is also applicable to H_2 and to gaging the tank fill level throughout the mission lifetime.

Another technique is to use liquid/vapor point detectors. These are located with the known liquid orientation in mind to give highly accurate fixed-point calibrations of liquid level and hence quantity. Typical liquid/vapor candidates are shown in Fig. 3-51.

Perhaps one of the more promising techniques to measure the He-II mass was presented at the 1985 AIAA Thermophysics Conference (Ref. 40). It consists of accurately measuring the temperature increase of the He-II in the tank resulting from a known heat input pulse. The mass is the amount of heat input divided by the temperature rise and specific heat at that temperature.

3.5 OVERALL TRANSFER APPROACHES

Much additional systems analysis is required prior to selection for optimum orbital transfer of He-II. Additional information is required about the characteristics of some of the system elements. In particular, engineering data are required about the FEP. The characteristics of the transfer line (primarily heat leaks) need to be established. The importance of the heat leak is not clear on a system level. To illustrate some of the systems which may be considered and their important features, a few simple systems will be described.

The first system (Fig. 3-52) illustrates the operation with a mechanical pump. It is assumed in these systems that a cold refill takes place, i.e., some residual He-II is present in the SIRTF so that a cool-down is not

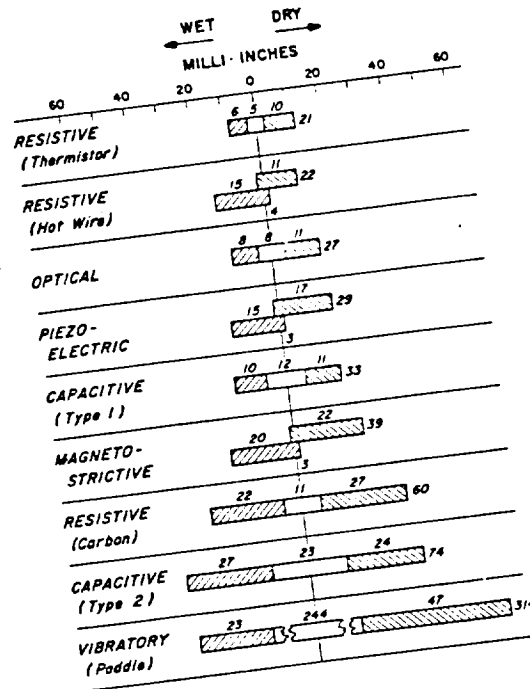


Fig. 3-51 Repeatability Data for Liquid/Vapor Point Detectors in Liquid Hydrogen (from *Adv. Cryogenic Engr.*, Vol. 9, p 420)

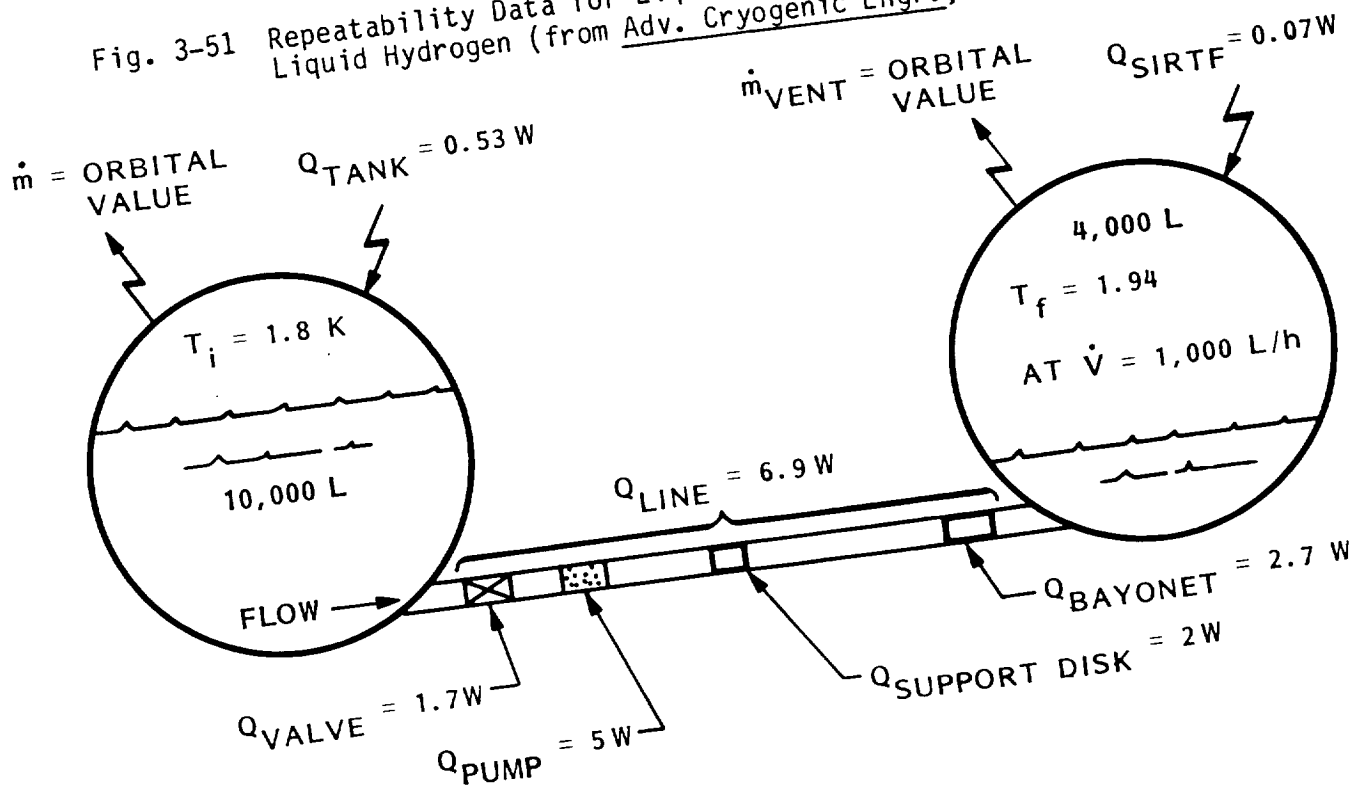


Fig. 3-52 Mechanical Pump System

necessary. For this and the following examples, it is assumed that the supply dewar which is sized for a cooldown and refill of SIRTf has a capacity of 10,000 L and the supply fluid is at 1.8 K. The 4000-L SIRTf tank is likewise assumed to be 1.8 K. The heat load to the supply tank is 0.53 W, which provides a lifetime of 2 years. This can be accomplished with existing technology. This design therefore has a depletion rate of 0.14 percent per day, so that an orbital operating time of 1 month prior to fill will produce a boil-off loss of 4 percent prior to fill. The assumed heat loads for the transfer line including 1 bayonet, 1 valve, and 6.1 m of line (3.05 m of rigid line and 3.05 m of flexible line) are based on commercial technology, and the assumed values are shown in Fig. 3-52.

The heat load of the SIRTf is based on the SIRTf Free Flyer Phase A System Concept, assuming a 3-year design life. The values for the supply and SIRTf tanks correspond to a venting system in which vapor cooling is present. If venting is discontinued, the heat rates will slowly increase to a substantially greater value. The total power input to the mechanical pump is assumed to be 5 W based on an extrapolation of the test data on the NBS centrifugal pump.

For this example the majority of the heat input is due to the transfer line and associated hardware. Calculations were made for this system to determine the feasibility of a nonvented transfer from tank to tank. It is assumed that the operational vent valves have been closed shortly before transfer and that the increase in heat rate due to the loss of vent gas cooling during the 4-h fill duration is negligible. It may be necessary or desirable to continue venting through the operational vents; further analysis is required.

Some of the key assumptions in the analysis were: (1) all heat from the valve and downstream goes into raising the temperature of fluid in the receiver dewar (no heat is transferred "upstream" to the supply dewar), and (2) the temperature of the supply dewar remains constant at 1.8 K. Preliminary calculations indicate a slight cooling of the He in this tank, but the supply tank temperature history was not completely analyzed.

Within the framework of these assumptions, the final temperature of the receiver tank (SIRTf) is 1.94 K for the nonvented operation. This result is not sensitive to the supply tank volume, since no significant temperature increase (or slight decrease) results. If a temperature of 1.8 K is required in the SIRTf (rather than the calculated 1.94), it can be achieved by venting the SIRTf down to 1.8 K with an associated loss of approximately 2 percent of tank volume, or by decreasing the supply tank temperature to 1.66 K. Reductions of the transfer line heat load can greatly reduce warming of the receiver tank fluid.

There are many ways to reduce the heat transfer to the transfer line below the present values used for commercial applications. NBS has suggested that using a bayonet joint in He-II may lead to difficulties, presumably because of the high liquid "thermal conductivity" of He-II or perhaps additional potential of thermal acoustic oscillations in He-II. The best way to reduce the heat load from the bayonets is to eliminate them. Lockheed has built vacuum-jacketed

line connections which completely eliminate the heat load due to these joints. This is accomplished by using a sliding or bellows type joint so that access to a vacuum tight connection for the transfer line is available.

In space the outer vacuum jacket is not needed, so access to seal the inner line is greatly simplified. An outer line is not needed in orbit for vacuum integrity, but may be needed for line protection. It is also obvious that the transfer line can be permanently attached to the supply tank, therefore eliminating the requirement for one connection or bayonet. The valves can be motor-driven cold valves which essentially eliminate the heat load.

Reduction of the line heat load over a length of approximately 6 m is more difficult. We expect that more extensive design and experimental work will reduce the heat load substantially, but this must be proven by tests. There should be no problem due to a gassy line (gas conduction) in the closed-off vacuum space, because the line should be vented in space and not sealed off. The other techniques to reduce line heat leak are a result of reducing the hot boundary temperature of the line. This can be done by proper thermal control surfaces on the line. Temperatures as low as 200 K may be attained by passive means. This may translate into a possible reduction of a factor of three based on a T^3 heat load dependence.

The other approaches which may be used to further reduce the heat load involve vapor-cooling or cooling with a separate cryogen (LN_2). For 10 W of cooling for 10 h (duration of liquid loading), the required amount of LN_2 is 4 lb, a modest amount.

Boil-off from the supply tank can also be used to vapor-cool the transfer line. If gaseous He is bled off the supply dewar and warmed to 70 K in the transfer line, only 3 lb are required. The required mass is negligible, and we believe that a simple technique to accomplish this can be developed. Based on these considerations, we believe that reductions as great as a factor of ten can be obtained for orbital transfer lines.

The nonvented mechanically pumped system has several desirable characteristics.

- (1) The system is relatively straightforward to analyze. The thermodynamics and fluid flow are based on well established techniques and principles.
- (2) The system is operationally simple. Elimination of venting precludes the requirement for a high flow rate vent system with its associated high throughput porous plug and valves. (A SIRTf cool-down may require this capability, however.)
- (3) Elimination of venting simplifies the mass inventory system. If the flow rate through the transfer line (or pump) is known by measurement with a flow meter, then the progress of the fill is known, since it is not necessary to measure the vent losses.

- (4) It is believed that the tank can be filled to 100 percent capacity, since the pump can be operated until the tank pressure suddenly rises to the pump discharge pressure due to the hydrostatic pressure. This is particularly useful since it will be clear when the tank is filled, again simplifying the difficult mass gaging problem. This hydrostatic pressure increase signaling the completion of the fill will probably also occur with the FEP.

The second system incorporates a FEP for transfer. The same heat leak assumptions as in the first system are made here for the tanks and transfer line. The heater input to the FEP is assumed to be 7.8 W based on the FEP analysis presented in the previous section. For this system there are significant uncertainties associated with the operation of the FEP. For this analysis, it is assumed that the FEP acts as an "ideal superleak." This nomenclature as utilized here indicates a condition in which the FEP acts as a perfect filter in which only the superfluid component of the He-II with zero entropy passes through. The result of this assumption is that the specific entropy of the supply tank increases, therefore leading to a temperature increase, while specific entropy of the receiver tank decreases, leading to a reduced temperature.

Since the operation of the FEP is dependent upon a temperature increase across the plug (higher downstream), the changes in temperature created by this mechano-caloric effect may eventually stop the pumping action of the FEP pump. To maintain the appropriate ΔT across the FEP for operation, the receiver and supply tanks must be respectively heated and cooled. In the selected example, cooling the supply tank to provide a constant 1.8 K temperature is achieved by venting at a constant rate of 1.71 g/s. The required heating of the receiver tank to maintain a temperature of 1.9 K is provided in part by the heat input to the transfer line plus an additional heater with 25.4-W heat input. The receiver tank is not vented.

In this example the transfer line supplies part of the required heat input and it is not obviously desirable to reduce the transfer line heat inputs. (A detailed analysis of the transfer line may indicate generation of vapor which may be undesirable, but so far this is not indicated.) The losses associated with this transfer technique are the 1.71 g/s venting of the supply dewar (4.3 percent of transferred mass). It may be necessary to vent the SIRT tank dewar to 1.8 K or use a colder supply tank to achieve the required SIRT tank temperature in a manner similar to that described with the mechanical pump system.

Many versions of the FEP-pumped system are possible, and the optimum choice will probably only be determined through extensive ground testing of the various approaches. Among the approaches which may be considered are:

Cooling the Supply Tank Only. Sufficient cooling by evaporation in the supply tank may establish the required temperature gradient across the plug for adequate transfer rates of He-II. Theoretically, this venting rate may be of sufficient magnitude to provide the required temperature difference across the

pump without the heat addition to the receiver tank. This approach has the advantage of eliminating the receiver tank heater and the FEP heater, but requires relatively high vent rates of the supply tank.

Heating of the Receiver Tank Only. If heat is supplied to the receiver to offset the mechano-caloric effect plus a small ΔT across the plug, then transfer can be affected without venting of either tank and without moving parts. Activation of the heater will control the flow rate. Achievement of the required final SIRTf temperature requires the appropriate choice of supply tank temperature or venting down the receiver.

There appear to be several options which will provide a 100 percent fill with relatively low transfer losses (0 to 4 percent) and relatively simple components. However, ground testing particularly with the FEP options will be required to verify the system operation. Table 3-12 summarizes some of the systems.

This comparison is for the refill of a cold tank only, and substantially different requirements may exist for refill of a warm SIRTf tank which could change the selection of the optimum system. The goal is to find an optimum system which will provide efficient and reliable refill of both warm and cold receivers.

Additional considerations for cooldown include variable flow rates over a large range (100 to 1000 L/h) for efficient cooldown, startup capabilities for a variety of fluid and temperature conditions, and pump pressure rise capabilities for cooldown flows of gas at relatively warm temperatures.

3.6 HELIUM-3 REPLENISHMENT

One element of the Multiband Imaging Photometer (MIP) may require cooling to the 0.1- to 0.3-K level for efficient operation. One approach which may provide the required temperature is an open-cycle He^3 container. This approach proposed as an alternative to the magnetic cooling approach would use a 100-L tank to provide cooling for 3 years in the 0.2- to 0.3-K range.

If this approach were selected, this cooler could be refilled during the same interval as the main tank. Two principal options were considered for this refilling. These are:

- (1) Carry LHe^3 to orbit and replenish as a liquid
- (2) Carry room-temperature gas and condense the fluid into the experiment tank

The main considerations are the complexities of transporting LHe^3 as opposed to the cooling requirements to condense the He^3 gas into the tank from a warm condition.

Table 3-12 SYSTEMS COMPARISON

System	Vent Rate	Electrical Heat Input	Comments
Mechanical Pump Transfer (Centrifugal Pump)	No venting of either tank required	5 W for pump power	0.14 K temperature increase above 1.8 K supply tank, 2 percent loss to vent down receiver to 1.8 K. Transfer principles well understood.
Fountain Effect Pump (FEP)			
System I Conventional FEP	Venting of supply tank at 1.17 g/s	7.8 W for FEP, 25.4 W to offset mechano-caloric effect	~ 0.1-K temperature rise for receiver. Easily cooled by venting. No moving parts. Test data required for FEP operation.
System II ΔT across plug obtained by venting supply tank only	Venting of supply tank at > 1.71 g/s	No heat input	No heat input, higher vent rate in supply tank.
System III ΔT across plug obtained by heating receiver tank only	No venting of either tank	> 33 W to receiver tank	Venting of tanks eliminated. Higher heat input to receiver, higher final temperature.

¹Transfer rate 1000 L/h

²Supply tank at 1.8 K

In the first option (transporting liquid) the He³ supply tank should be as cold as possible to prevent excessive losses in achieving 0.2 K. One approach is to guard the tank with the He³ supply He-II supply dewar. The He³ is therefore at 1.8 K and has a corresponding vapor pressure of 102.5 torr. One primary consideration is management of the liquid. The kinematic surface tension of He³ is shown in Fig. 3.41, which indicates that it is lower than He⁴. Since there is only a requirement to transfer 100 L, the capability of a gallery device will be slightly higher than He⁴, even though the kinematic surface tension is lower. This is primarily due to the supply tank being much smaller and the hydrostatic head that the capillary device must overcome being lower. During transfer, the He³ receiver tank should be thermally connected to the SIRTf He-II tank. A heater on the supply could be used to slightly

raise the temperature and pressure of the He^3 . This provides and maintains a positive pressure to drive the liquid. Once the receiver tank is filled and stabilized at 1.8 K, it is thermally decoupled. This thermal coupling and decoupling can be provided by a thermal switch.

We also considered supplying the He^3 as a supercritical fluid ($P_C = 1.15$ atm, $T_C = 3.32$ K). This form of storage eliminates the requirement for the liquid management device; the tank could be loaded with LHe^3 at 1.8 K (provided by the He^4 supply tank) and allowed to warm to above the critical pressure for the filling operation. A small heat input is required to maintain the tank above the critical pressure during withdrawal. The supercritical fluid is condensed to 1.8 K in the receiver tank as in the other cases. The amount of He^4 utilized to condense 100 liquid liters of supercritical He^3 is approximately 60 liquid liters based on the specific heat of gaseous He^3 and the heat of condensation and vaporization of the two heliums.

An alternative to condensing He^3 in the receiver tank is to thermally ground the supply line to the SIRTf tank. Condensation can take place at this location, and the collapsing pressure will provide the driving force between this location and the supply tank. Once the liquid has condensed it must be transferred to the receiver tank. The most practical method is a wicking action such as in a heat pipe. This can simply be specially designed grooves in the tubing. The receiver tank will be filled with a metallic foam to retain liquid and provide vapor venting during normal operations. The fill line wick can be connected to this foam so that it will drain the line and fill the tank. Another option is to use a passive liquid/vapor separator in the condensing region.

Supplying the He^3 as a warm (room-temperature) gas greatly simplifies the supply tank design since it requires no thermal protection. If 300-K gas is condensed into its receiver tank by cooling from the He^4 supply, 5000 L would be required to cool and condense 100 liquid liters of He^3 . This excessive amount is based on use of the heat of vaporization of the He^4 .

A counterflow heat exchanger using the vented He^4 gas during with SIRTf fill will greatly reduce the required quantity. The inlet line for the He^3 could be thermally grounded to the vapor-cooled shields or could travel the same route as the He^4 vent line, therefore effecting a counterflow heat exchanger. In the limit, for a perfect counterflow heat exchanger, 130 L of liquid He^4 are required to condense 100 liquid liters of He^3 . The size of the gas storage bottle required is a primary consideration and depends upon the storage pressure selected.

Section 4

INSTRUMENT CHANGEOUT STUDIES

4.1 INTRODUCTION

The current SIRTf consists of three scientific instruments [infrared spectrometer (IRS), multiband imaging photometer (MIP), and infrared array camera (IRAC)] plus five cryogenic mechanisms (fine guidance sensor, beam splitter, secondary mirror, aperture door, and cryogenic valves) which have active elements that may require servicing or changeout on orbit. It is desirable to accomplish this modular changeout cold to avoid warming up the entire SIRTf if cryocontamination can be avoided. Large quantities of He are required for cooling if SIRTf is warmed up. In addition, thermal cycling of the other scientific instruments that are not changed out should be minimized.

Weight, cost, and complexity increase with cold changeout as opposed to warm changeout. This section provides a preliminary comparison of warm versus cold changeout concepts so that preliminary judgments can be made about the most suitable approach to follow. Definition of the scientific instruments is not detailed enough now to look at changeout designs tailored to each instrument. Consequently, generic approaches are described. A brief description of possible changeout approaches for the five cryogenic mechanisms (cold where possible) is also provided.

4.2 DEFINITION OF SCIENTIFIC INSTRUMENTS AND CRYOGENIC MECHANISMS

Table 4-1 provides characteristics of the three scientific instruments selected to date for SIRTf. The instrument heat load data are incomplete on two of the experiments, and the layout and dimensions of the experiments are also not well defined. The location and operating temperature of the five cryogenic mechanisms are given in Table 4-2.

4.3 CANDIDATE INSTRUMENT CHANGEOUT APPROACHES AND COMPARISONS

4.3.1 Scientific Instrument Changeout

Two warm and two cold changeout concepts were developed. A description of each concept follows.

Concept 1 (Warm Changeout)

Concept 1 is shown in Figs. 4-1 through 4-5. Access to the scientific instruments is provided with the SIRTf at a temperature of 270 K or higher by opening the vacuum shell latches (No. 1) and activating the three motorized translation mechanisms. The Multiple Instrument Chamber (MIC)/telescope subassembly rolls out on three rails located on the inner diameter of the He

Table 4-1 INSTRUMENT DESCRIPTION

Instrument and Investigator/ Institution	No./Type	COLD MODULES						WARM ELECTRONIC BOXES					
		No. of Optical Viewing Paths/ Viewing Mode	MIC Angle (deg)	Dimensions (m)	Temp. (K)	Peak Heat Load (mW)	Wt. (kg)	No.	Max. Power (W)	Size (m)	Wt. (kg)	Total No. of Wire Feed-throughs to Cold Modules	Max. Operating Bit Rate (kbps)
IR Spectrometer (IRS) J. Houck / Cornell University	4 Modules	1 (individual viewing)	90	< 1			TBD	TBD	50	TBD	20	~300	6.4
	Spectrometer A (4-30 μm)				7	5	TBD						
	Spectrometer B (28-114 μm)				2	5	TBD						
	Spectrometer C (28-114)				2	5	TBD						
	Spectrometer D (114-200 μm)				2	5	TBD						
Multiband Imaging Photometer (MIP) G. Rieke/ University of Arizona	Additional components serve all 4 modules												
	• Grating angle encoder	-	-	-	70	5	TBD						
	• Stepper motors	-	-	-	7	30	TBD						
	• Torque motor	-	-	-	7	5	TBD						
Infrared Array Camera (IRAC) G. Fazio/ Smithsonian Astrophysical Observatory	3 Modules	1	60	< 1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	200	300
	Small silicon array (individual viewing) Germanium array				TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	Bolometer				TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	1 Module	3 (simultaneous viewing)	60	0.5 x 0.3	Detectors 7 Actuators TBD	Detectors < 108 Actuators TBD	26.9	1	60	TBD	6.6	146	30
	• Band 1 (2-5 μm) • Band 2 (5-18 μm) • Band 3 (18-30 μm)												

Table 4-2 CRYOGENIC MECHANISMS

Instrument	Location	Operating Temperature (K)
Fine Guidance Sensor (FGS)	Center line, rear of MIC	100-150
Beam Splitter (BS)	Center line, front of MIC	2
Secondary Mirror (SM)	Center line of aperture, interface of forward/aft baffles	2
Cryogenic Valves (CV)	On HE-II tank or normal He tank (if used for ground hold)	2-4

torus tank. Three rails permit up to 120-deg instrument segments to be removed or installed. The only joints broken within the dewar are shrink-fits, vapor-cooled shield (VCS) joints, and a mitred insulation joint. All wiring for the MIC instruments penetrates the back end of the vacuum shell to the warm instrument electronics boxes and remains intact. All plumbing, including vapor-cooling lines and instrument wiring to the He dewar, is kept intact as well. Power and data lines from the warm electronics to the spacecraft telemetry system may either be disconnected or have service loops designed in them.

In this concept the He tank is supported axially and in torsion by six forward PODS-IV struts. The MIC/telescope assembly is supported axially and in torsion by six rear PODS-IV struts. Lateral and tilt loads are taken out by all 12 PODS-IV struts through three channels. This design prevents putting thermally induced strain into the struts during tank or vacuum shell cool-down. The six struts on the tank are free to move independently of the six struts attached to the MIC, by translation of the rollers in the channels. Supports must be able to take both tension and compression loads, thus effectively eliminating tension bands as a candidate support system for this conceptual design. It is also possible to remove and service or replace the entire MIC with all instruments installed by opening latches 2 or 3 (Figs. 4-2 and 4-3) and disconnecting the electrical connectors.

To close the dewar following servicing, the three motorized translation mechanisms are activated. As the dewar closes, the astronaut may check and guide the VCS pins into their mating holes (Fig. 4-1, Detail A). By using nine pins (three per VCS) of different lengths, each pin entry can be verified visually. Clearance is large (1.8 mm) between aluminum and titanium rings on the VCS when warm, providing adequate clearance. The rings seize upon

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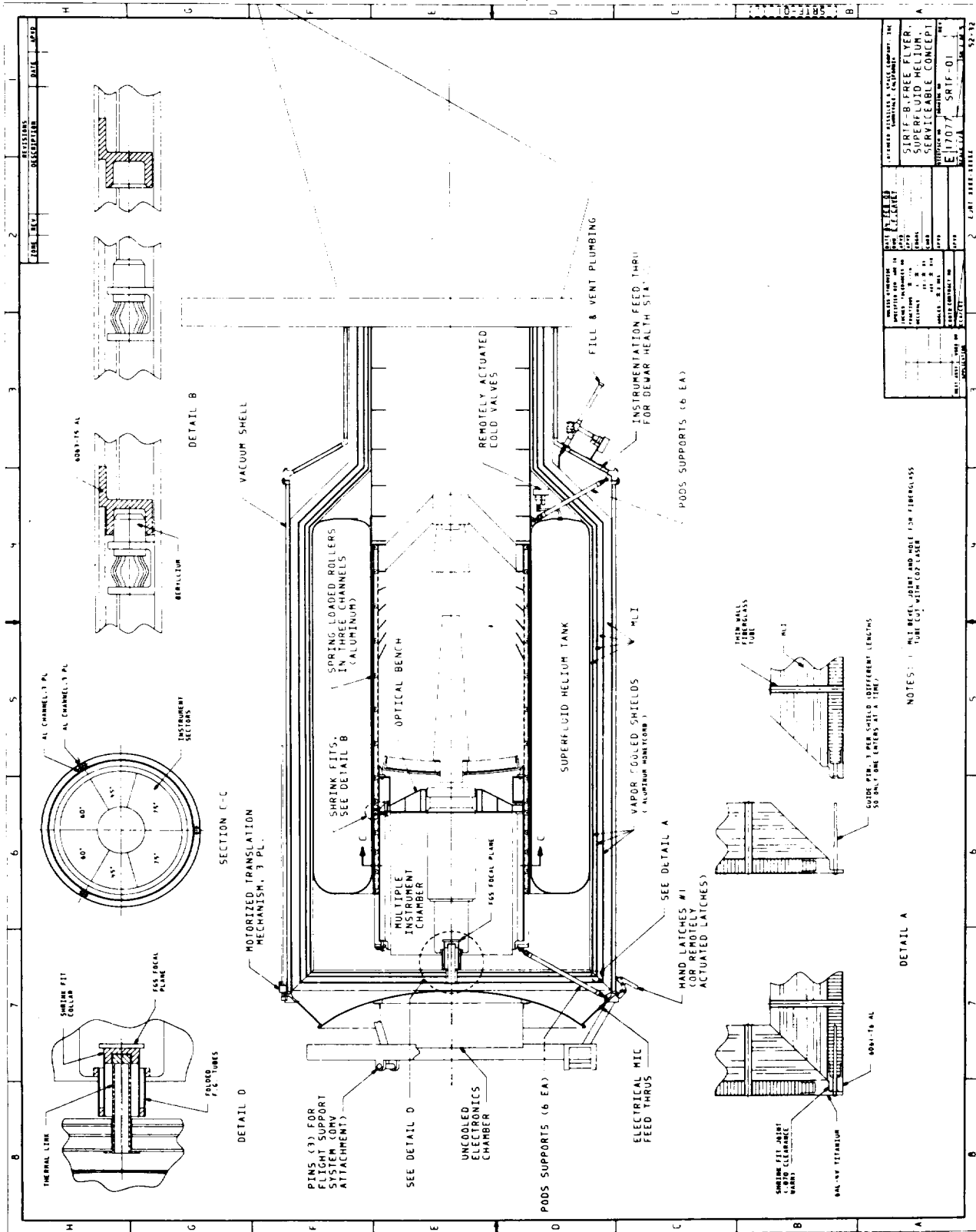


Fig. 4-1 Concept 1 (Warm Changeout)

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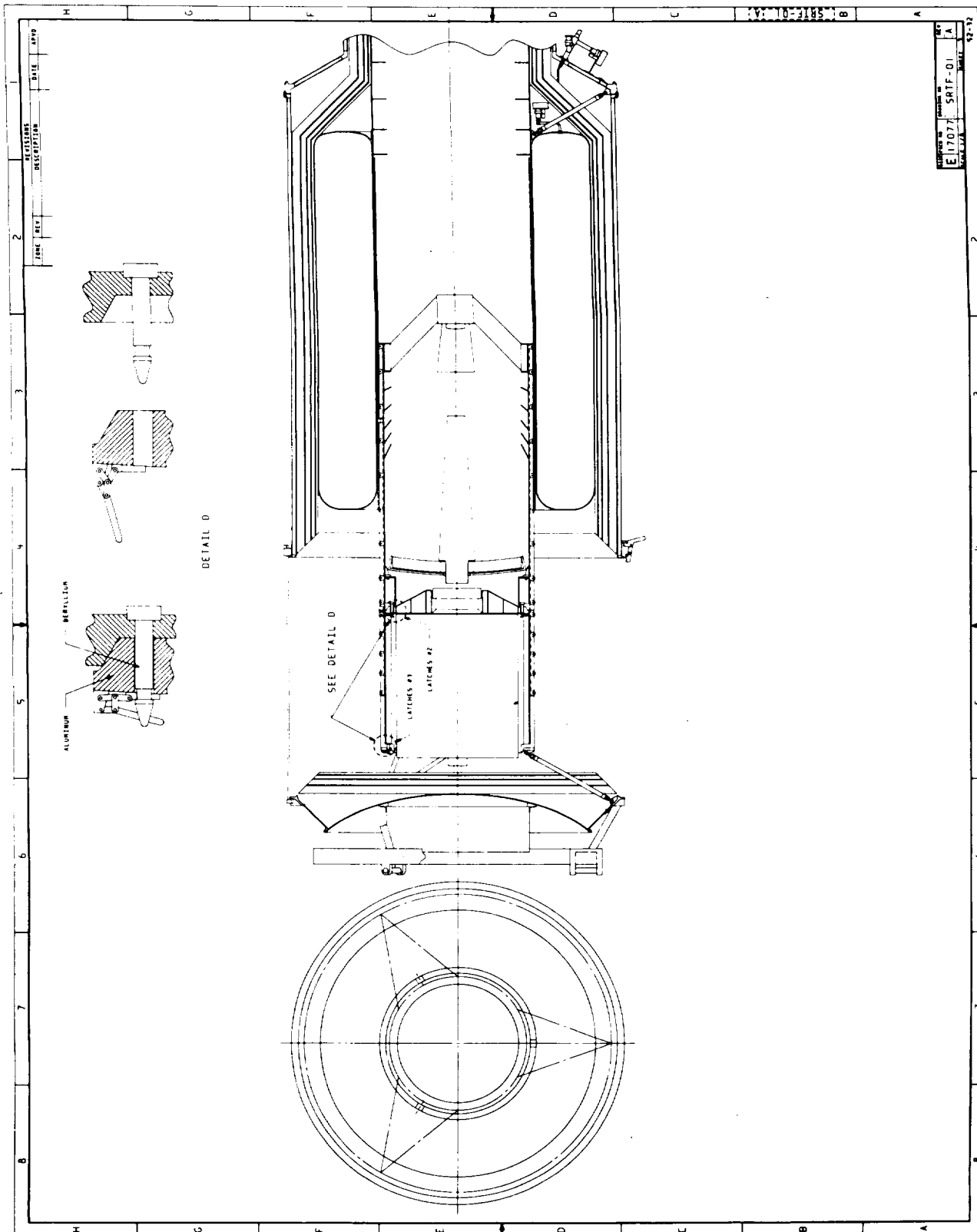


Fig. 4-2 SIRT Opened for Instrument Changeout

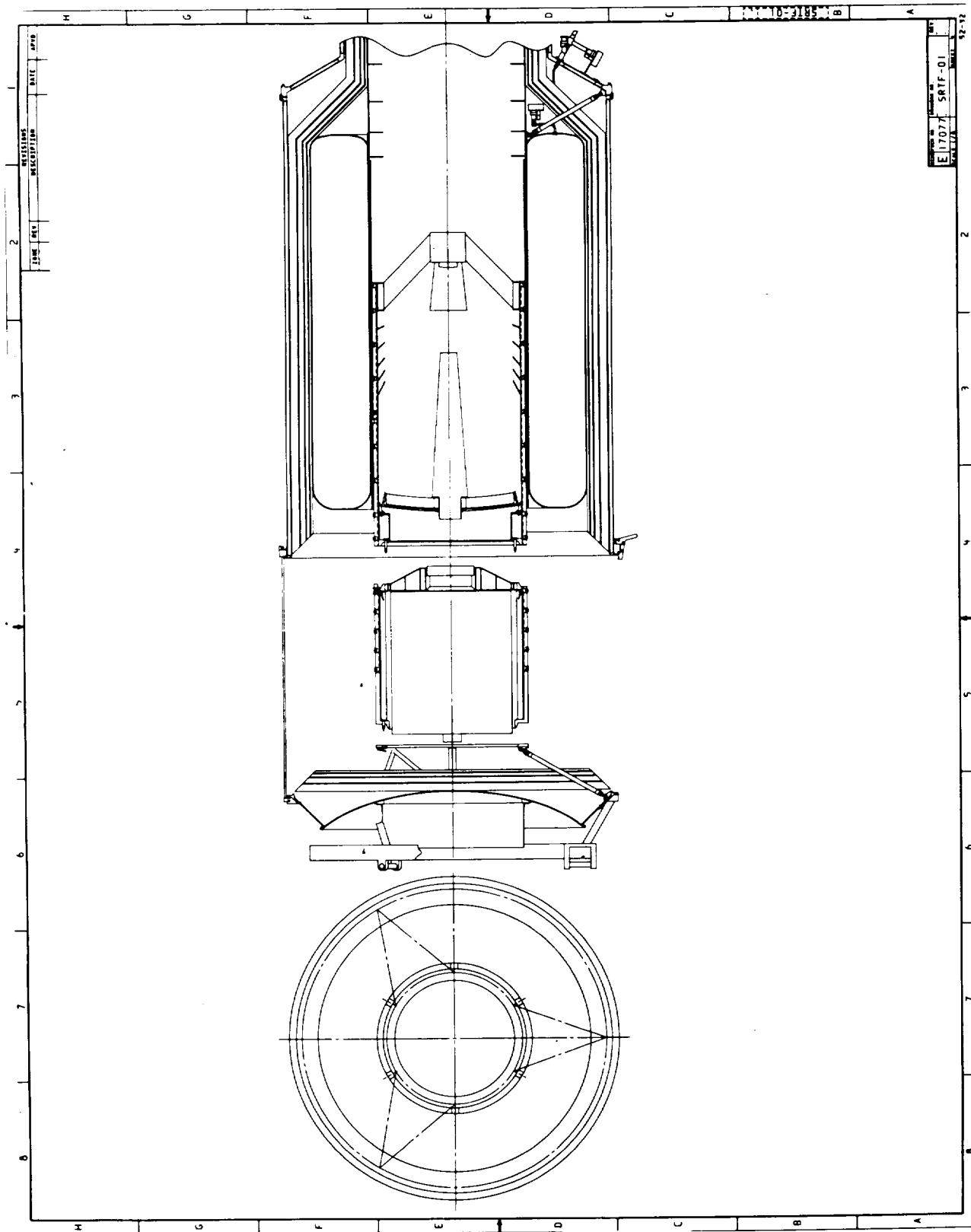


Fig. 4-3 MIC Disconnected for Removal

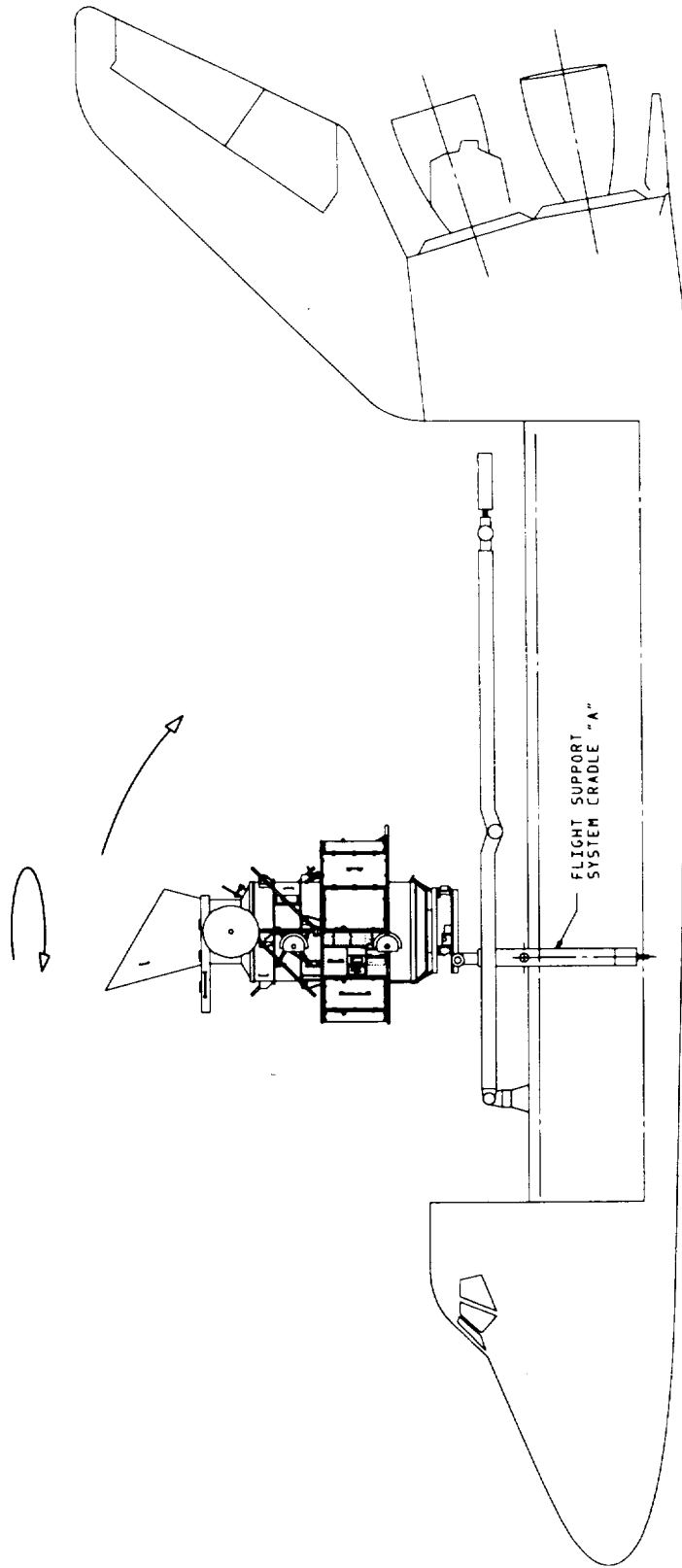


Fig. 4-4 SIRTIF Docked in Shuttle Bay on Flight Support System

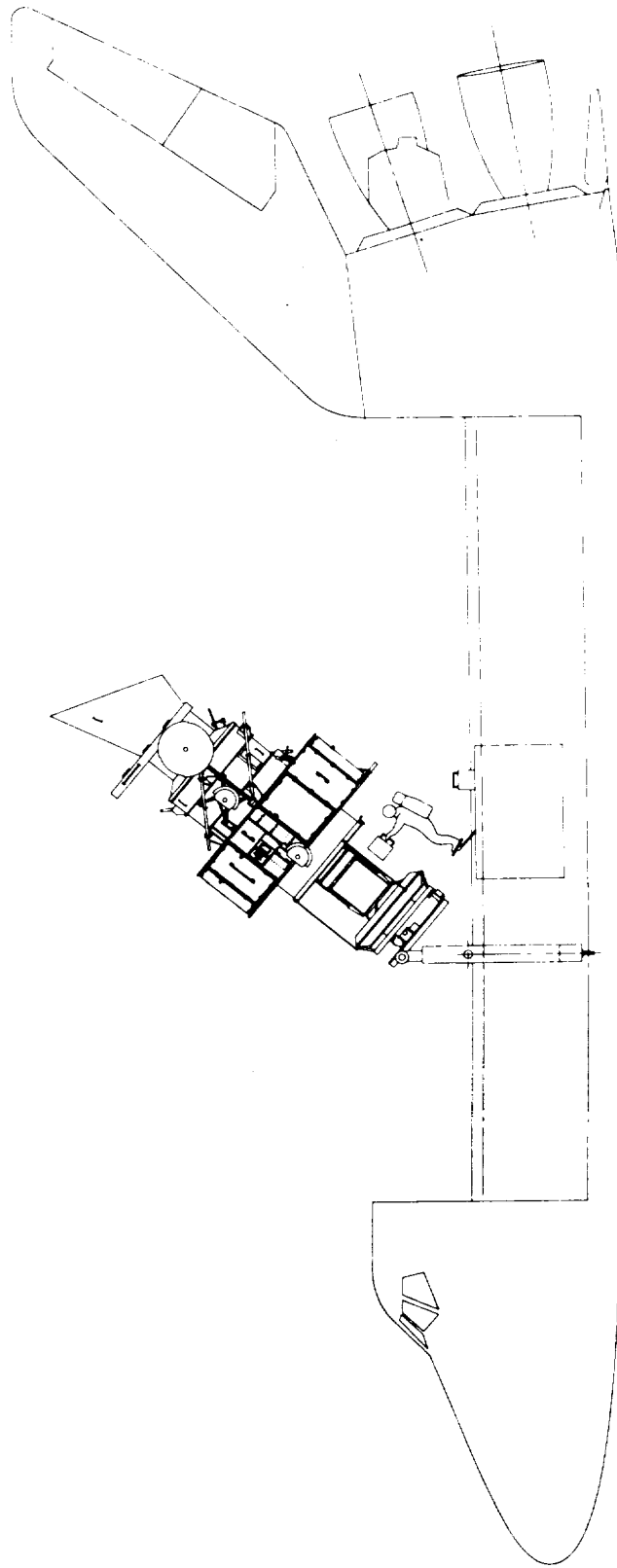


Fig. 4-5 Orbital Replacement of Scientific Instrument

cool-down, providing structural support and minimal interfacial thermal resistance across the joint. The instruments are cooled conductively from the He tank using shrink-fits of the type shown in Fig. 4-1, Detail B.

An instrument changeout onboard the shuttle is illustrated in Figs. 4-4 and 4-5. SIRTf is mounted in the shuttle on the Cradle-A flight support system used for the Solar Maximum Mission and Space Telescope (Fig. 4-4). This system allows SIRTf to be tilted or rotated about its longitudinal axis. Figure 4-5 shows an astronaut replacing a pie-shaped instrument in the MIC in accordance with procedures already developed for Space Telescope and other programs. The corresponding warm electronics box can be removed from the aft of the vacuum shell as well. The entire MIC is being removed and replaced in Fig. 4-5 using the remote manipulator system (RMS).

Concept 2 (Warm Changeout)

Concept 2 is a variation of Concept 1; only the back end (consisting of the warm electronic boxes, vacuum shell, MLI, and VCSs) rolls open as shown in Fig. 4-6. The MIC and telescope remain in place inside the He torus tank. The scientific instruments plus the fine guidance sensor (FGS) and beam splitter (BS) are mounted on telescoping rails. The instruments are rolled out the back end for servicing or changeout from the side. The FGS/BS are serviced in a similar manner. Two shrink-fits provide a 2-K and 7-K heat station at the forward end. The electrical leads require a service loop to the warm electronics. In this concept, vent gas can be ducted directly to the primary mirror to speed up cool-down, then to the forward baffle.

Concept 3 (Cold MIC Changeout)

Figure 4-7 illustrates how the entire MIC can be changed out cold in orbit. A separate MIC with a full complement of new instruments, FGS, BS, and removable vacuum shell with MLI is loaded on the ground with He-II. The MIC and separate HE-II tank are supported with six PODS struts. It is transported to orbit along with a special piece of ASE (translation rail fixture). SIRTf is supported off its side, and the ASE and new MIC are attached to SIRTf (Step 1). The latches on the SIRTf vacuum shell are released, and the old MIC is rolled out and removed with the remotely operated arm. (Step 2). The vacuum shell/MLI is removed from the new MIC assembly and installed on the old MIC assembly (Step 3) with the remotely operated arm. Free standing radiation shields surround the MIC and end of the SIRTf to reduce the radiation heat load during changeout and protect surfaces from cryocontamination (except in the aperture region). Special removable covers in the aperture region may be required. The new MIC is rolled in, the vacuum shell latched, and the ASE removed (Step 4). The time SIRTf and new MIC are exposed to ambient vacuum should be kept as short as possible, i.e., a half hour to minimize the heat load and exposure to cryocontamination. The MIC He-II tank cools the instruments to 2 K and 7 K and intercepts the parasitic heat load through the back end of the MIC. The telescope He-II tank cools the remainder of SIRTf.

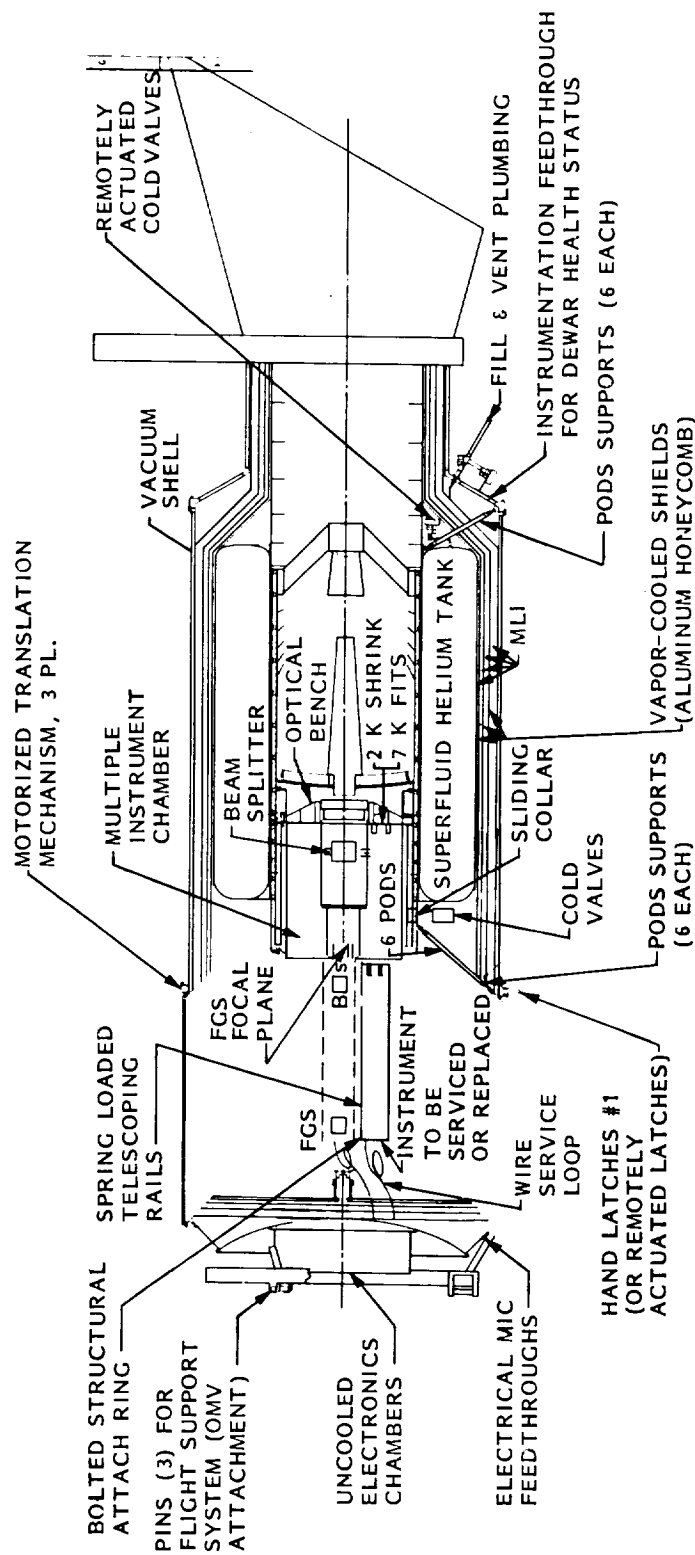


Fig. 4-6 Concept 2 (warm Changeout)

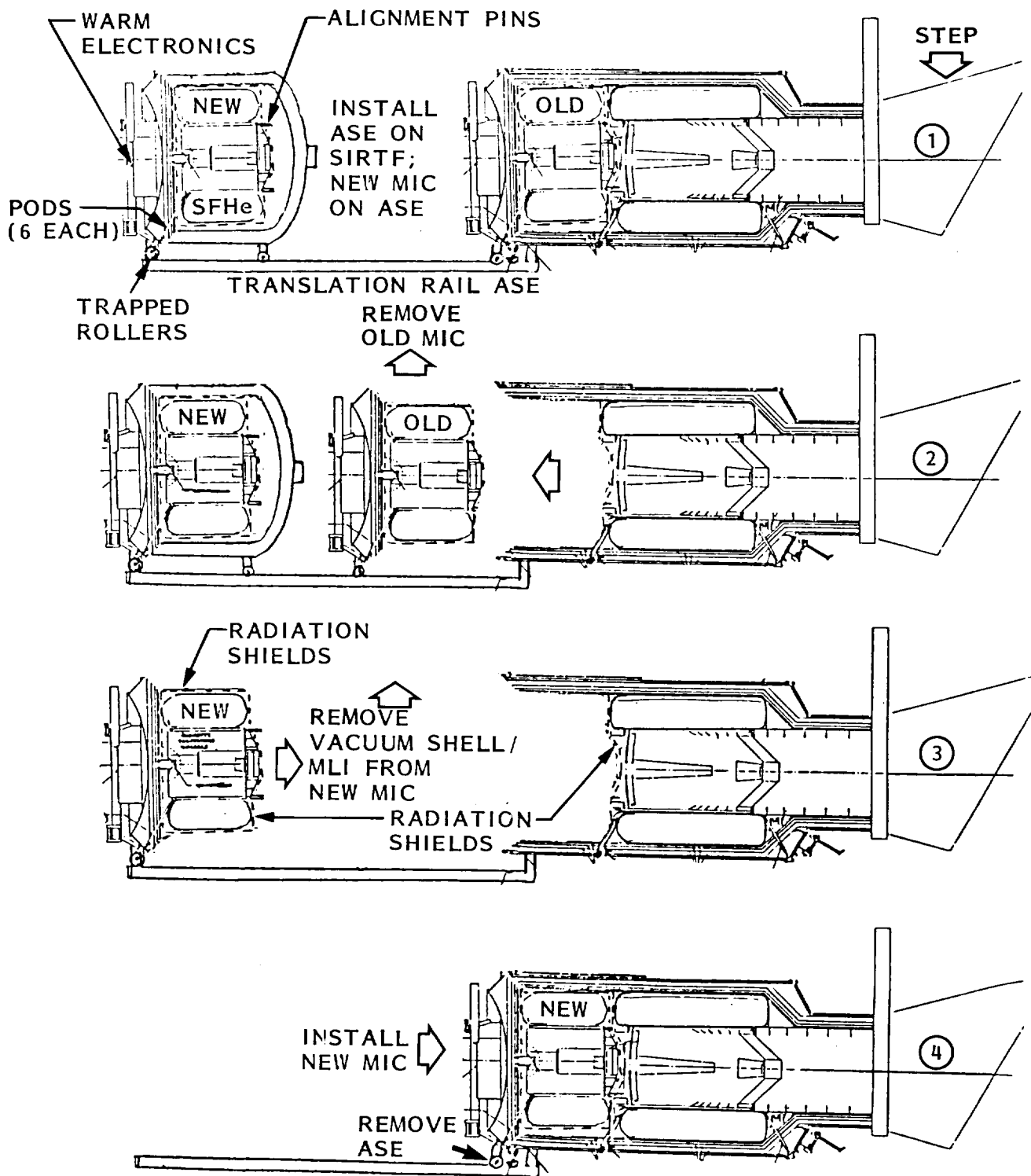


Fig. 4-7 Concept 3 (Cold MIC Changeout)

This approach is presented only as a concept. Substantially more work is required to assess its practicality. Serious potential problems must be carefully evaluated relative to contamination, heat rate, and safety issues. Since this approach exposes the cold MIC assembly aperture to the environment, there is concern regarding contamination of condensible gases during the exposure period. An aperture cover plus He purging may be required to preclude or minimize contamination. Careful procedures and handling devices will be required to ensure that astronauts do not contact cold surfaces at any time. In addition, thermal analysis is required to determine if the heat input to the MIC assembly through the radiation shields is acceptable for the duration of mating with the telescope.

Concept 4 (Individual Cold Instrument Changeout)

Concept 4 uses the same instrument changeout approach of concept 3; however, individual instruments or the FGS/BS can be changed out as shown in Fig. 4-8. An ASE translation rail is attached to the instrument requiring changeout. The same general approach described in Fig. 4-7 is followed. The instruments are removed 90 deg to the SIRTf axis, while the FGS/BS are removed along the SIRTf axis. The ability to remove only a malfunctioning instrument while not touching the other instruments or the rest of SIRTf is a strong advantage of this design. However, the He tank is sized mainly by the instrument heat load plus the small parasitic heat load through the top vapor-cooled end section. The instrument heat load (and consequently He tank size) can vary widely as discussed in a later section, a potential drawback to this approach. A way

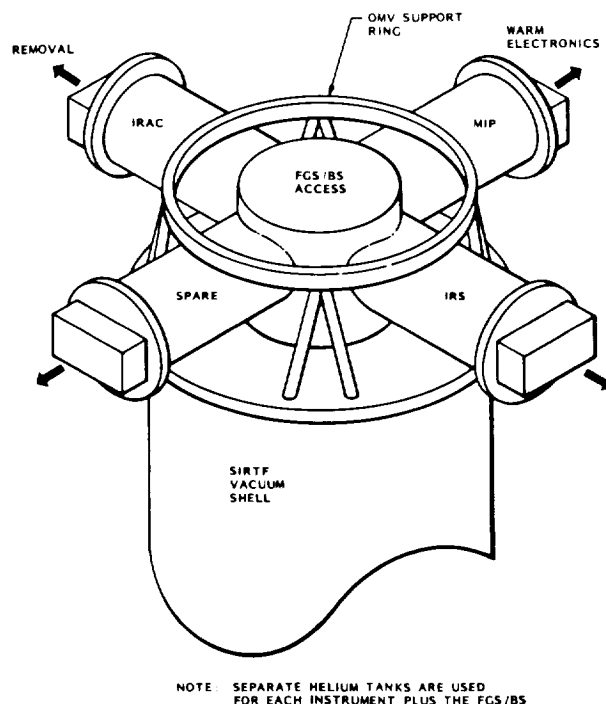


Fig. 4-8 Concept 4 (Individual Cold Instrument Changeout)

around this problem is to remotely cold-couple the 2-K and 7-K instrument heat stations to the 2-K and 7-K telescope tank heat stations, i.e., active couplings, compressing high-purity copper wool pads together, etc. The same concerns expressed for concept 3 apply here.

4.3.2 Scientific Instrument Changeout Comparisons

Both qualitative and quantitative comparisons were made between the four concepts. Table 4-3 shows comparisons for (1) instrument or cryogen mechanisms servicing, (2) photon integrity, (3) contamination control, (4) routing of cooling gas, (5) SIRTf support, (6) PODS support complexity, and (7) VCS attachment complexity. Alignment problems are discussed later.

Tables 4-4 and 4-5 show weight and length increases and lifetime decreases as compared to a nonserviceable design. From a technical standpoint, all four concepts appear feasible to develop, although considerably more development is required.

Of the two warm changeout concepts, concept 2 appears superior to concept 1, mainly because of the ease with which vent gas can be routed to the telescope and forward baffle for more efficient rapid cooling. Advantages and disadvantages in other areas in Tables 4-3 and 4-4 about balance, including weight, length, and lifetime changes.

For the two cold concepts, concept 4 appears superior to concept 3 for the following reasons. Ability to change out one or more instruments (as in the case with concepts 1 and 2) instead of being forced to change all the instruments at once is a strong advantage. Also, the instrument changeout occurs from the side so the SIRTf can be supported off the back end (rather than the side as in concept 3). In the area of number of PODS and VCS complexity, concept 3 is superior. Concept 4 requires less axial length for BS/FGS changeout (2.7 m) versus concept 3. Differences in lifetime decreases are not significant. These decreases are due to the possible opening of separable MLI mitred joints as shown in Fig. 4-9. A gap of 0.75 cm was arbitrarily selected based on a postulated worst case. The parametric effects of other gap sizes in Fig. 4-9 show that even larger gaps do not have a large effect on lifetime. In the calculations, it is assumed that there is no gap in the VCSs due to the shrink-fit, stepped construction.

The cost impact of adding instrument changeout capability and cryogenic mechanisms servicing was normalized against the nonserviceable baseline (without the spacecraft). The preliminary cost estimate includes the added SIRTf development and fabrication costs plus the ASE costs for concepts 3 and 4.

Table 4-3 QUALITATIVE COMPARISON OF INSTRUMENT CHANGEOUT CONCEPTS

	Warm Changeout		Cold Changeout	
	Concept 1	Concept 2	Concept 3	Concept 4
Access for servicing instruments				
• Structural mount	1	2 Requires long-handled tool	1	1
• Electrical connectors	1	2 Requires service loop	1	1
• Beam path alignment	1	2 Visual check of alignment	1	1
• 2-K connector	1	1 not possible	1	1
• 7-K connector	1	1	1	1
Cryogenic mechanisms				
• Fine guidance sensor	2 May have to remove instrument for side access	1	1	1
• Beam splitter	2	1	1	1
• Secondary mirror	1	1	1	1
• Cryogenic valves	1	1	Not possible	Not possible
• Aperture door	1	1	1	1
Remove entire MIC	1	Not possible	1	Not possible
Photon integrity	1	1	1	1
Contamination control	2 Greater possibility of optics particulate contamination from rollers	1	3	3
7-K station and forward baffle cooling (vent gas routing)	2 Direct routing of vent gas not possible; conductive cooling through shrink fits	1	1	1
OMV, shuttle, or space station support points	1	1	2	1
PODS support complexity	1	2 Requires sliding collar, one end	3	4
Vapor-cooled shield attachment complexity	1	1	2	3

1, 2, 3 - Relative ranking
1 - Most desirable

Table 4-4 QUANTITATIVE COMPARISON OF INSTRUMENT CHANGEOUT CONCEPTS TO A NONSERVICEABLE DESIGN

CONCEPT NO. →	WARM CHANGEOUT		COLD CHANGEOUT	
	1	2	3	4
Δ Weight Increase SIRTF ● kg ○ Percent of Total(2) ASE ● kg	72 2.2	79 2.4	202 6.2	461 14
			TOTAL 432 634	72 533
Δ Length Increase Required For Servicing ● m ● Percent of Total(3)	1.7 20	1.7 20	3.7 44	BS/ Instru- FGS ments(4) 1.0 0 12 0
Δ Lifetime Decrease (5) ● Percent of Total	0.6	0.6	0.6	1.1
Minimum Tank Sizes For Instrument Cooling(6), Liters	-	--	>398	IRS 81 MIP TBD IRAC > 317

NOTES:

- (1) See Table 4-5 for detailed weight breakdown
- (2) Nonserviceable SIRTF weighs 3240 kg
- (3) Nonserviceable SIRTF length is 8.5 m
- (4) Instruments removed radially; 2.5-m clearance required
- (5) See Fig. 4-9
- (6) If the instruments are cold coupled to the telescope tank, this restriction goes away.

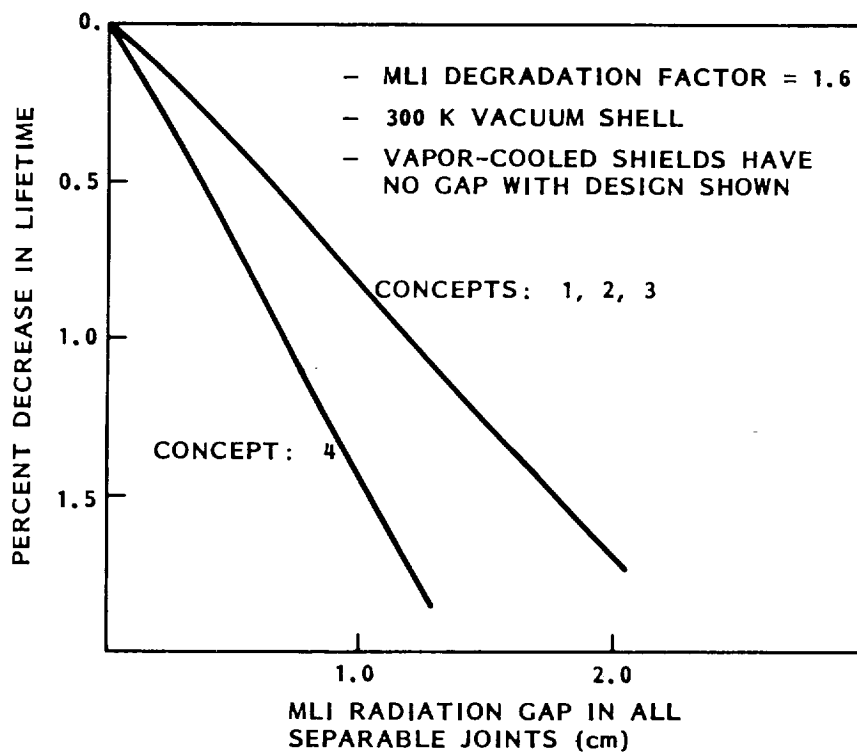


Fig. 4-9 Effect of MLI Gap Size in Separable MLI Joints in SIRTf Lifetime

Concept		Percent Cost Increase Over Nonserviceable Baseline Design
Warm	1	+6
Changeout	2	+6
Cold	3	+15
Changeout	4	+17

There is no significant difference between the two warm changeout concepts or between the two cold changeout concepts. Going to a cold changeout versus warm adds about 10 percent to the cost of the program minus the spacecraft.

The impact on STS costs was driven more by length increases required for launch rather than increased weight. The additional cargo bay volume required may be decreased some by more compact packaging designs for the SIRTf, replacement instruments, and ASE.

Concept	Percent Increase in STS Costs Versus Nonserviceable Design
---------	--

1	15
2	15
3	35
4	8

Concept 3 has the highest impact on STS costs due to the extra length required for the replacement MIC and ASE.

4.3.3 Optical Realignment After Changeout

The alignment errors introduced during the changeout procedure affect both the optical system boresight alignment and the optical image quality. The SIRTf boresight alignment requirements are tight, with an alignment tolerance of ± 0.1 arcsec. This operational requirement is not applicable to the optical system before cool-down and calibration. Therefore, the boresight alignment requirement does not become a driving factor for the installation alignment requirements as long as the calibration procedures can adequately compensate for any installation misalignments.

To define the problem of estimating a reasonable precalibration boresight alignment error as well as the image quality reduction associated with installation alignment errors, the expected alignment error is compared to the total optical system field of view. The SIRTf baseline design has a 7-arcmin field of view. If there is an alignment error in the range of 1 to 5 percent of the SIRTf total field of view, for the purposes of this preliminary analysis this can be viewed as a simple shift of the viewing field. From this point of view the optics are no longer seeing ± 3.5 arcmin but are seeing for example $+3.68/-3.33$ arcmin for the 5 percent case and $+3.53/-3.47$ arcmin for the 1 percent case. Thus, the optical performance will degrade at the outer edge of the field of view by the amount associated with simply extending the field another 1 to 5 percent. This amount of degradation should be small.

Similarly, the boresight alignment calibration should be able to compensate for some percentage of the total SIRTf field of view. For example, 1 percent of the 7-arcmin SIRTf field of view corresponds to 4.2 arcsec of alignment error or 0.415 mm of image motion in the SIRTf focal plane. For the MIC chamber misalignment to produce such an alignment error in the SIRTf focal plane, a 2.9-arcmin tilt error (i.e., 0.08 mm of wedge height over 10 cm) or a 0.415-mm translation error would be required during the installation of the MIC system.

For the f/24 SIRTf baseline design, the diffraction depth of focus is approximately ± 2.9 mm. Thus, MIC installation alignment position errors in

the ± 0.5 -mm to ± 3.0 -mm range will produce boresight alignment errors of about 1 to 5 percent of the field of view and will remain within the diffraction-limited depth of focus. Similar values apply if the interface is at the individual scientific instrument. At this point in the preliminary optical analysis of the SIRT FGS and instruments changeout alignment tolerance requirements, the mechanical requirements for installation do not appear to present any critical design, fabrication, or installation problems.

4.3.4 Cryogen Mechanisms Changeout

Table 4-6 summarizes the access available for changing out or servicing the cryogenic mechanisms. Concepts 3 and 4 do not have access for cryogenic valve changeout. Concepts 1 and 2 (warm changeout) have an added advantage over concepts 3 and 4 (cold changeout) in that minor servicing of the mechanisms as well as changeout can be accomplished. Only changeout is possible for concepts 3 and 4. Changeout of the secondary mirror through the aperture is difficult due to the long reach and special tools required, and it introduces contamination problems for the primary mirror. Shrink fits are used for good thermal contact for a warm changeout. Gold-coated bolted surfaces are used in a cold changeout. A single bolt is used to separate both the structure attachment and electrical connectors per the Space Telescope design.

4.4 RECOMMENDATIONS

More detailed conceptual design plus development and transportation cost analysis are required before a final changeout approach can be selected. However, based on the work performed to date, concepts 2 and 4 appear to be the leading candidates and should be studied in more detail.

Table 4-6 ACCESS FOR CHANGEOUT OF CRYOGENIC MECHANISMS

Concept →	Warm Changeout		Cold Changeout	
	1	2	3	4
Fine Guidance Sensor (FGS)	Side	Rollout back; side	New FGS and BS included	Roll out back; replace
Beam Splitter (BS)	Side	Rollout back; side	In MIC replacement	FGS/BS as a unit
Secondary Mirror (SM)	Through Aperture			
Aperture Door (AD)	External, Side			
Cryogenic Valves (CV)	Side, end of tank	Side, end of tank	Not possible	Not possible

Section 5

OPERATIONS ANALYSIS

5.1 STICCRS GROUND RULES AND ASSUMPTIONS

The ground rules and constraints listed below were derived from the STICCRS Statement of Work, the SIRTF Free Flyer Phase A System Concept Definition, and familiarity with NASA-Ames objectives, preferences, and concerns.

- SIRTF orbit altitudes considered are 600 to 700 km, with inclinations of 28.45° and 98.2°
- SIRTF Free Flyer Phase A System Concept Description is the starting point for analysis
- Cryogenics must be resupplied for either a warm or cold SIRTF
- The SIRTF ground handling and system test equipment are not subjects of this study
- Cryogen resupply GSE and logistics support are subjects of this study
- Access to the SIRTF is provided by direct injection of the STS orbiter or by OMV based in the orbiter or the space station. The SIRTF spacecraft has no integral propulsion for rendezvous with the orbiter or space station
- Astronaut safety shall be a major consideration in all operational approaches to SIRTF servicing

The following list of factors that we presumed at the study outset are less firmly based in NASA documentation than are the Ground Rules and Constraints. They are presented to indicate all the factors which have limited the approach and the concepts developed in this STICCRS study.

- SIRTF spacecraft orbital replaceable unit (ORU) changeout is outside the scope of this study, but typical spans are included in mission timelines
- Scientific instrument changeout is not included in this section. (See Section 4.) Lack of definition of engineering details of these payloads precludes derivation of accurate timelines for their changeout tasks
- For this study the SIRTF cryogen replenishment starts after docking. That is, the STS launch, ascent, and OMV operations are considered only to the extent of examining the shuttle orbiter and OMV performance to identify constraints on the resupply mission
- Replenishment mission support by ground personnel and facilities will be accomplished by conventional payload operations control center (POCC) and is not part of this study
- Post-replenishment activities, e.g., SIRTF and spacecraft flight readiness testing, is out of the scope of this study. Appropriate timespans are included in the overall mission plan

- After cryo replenishment, the low-inclination SIRTf free flyer will be inserted into a convenient orbit having the original inclination and altitude, but a new orbit nodal location. The sun-synchronous SIRTf will be inserted into a comparable sun-synchronous orbit

The SIRTf Phase A Free Flyer System Concept Description was the source for the SIRTf mass, while the OMV office at MSFC was consulted for OMV mass. Baseline masses were assumed for other items – the cryogen replenishment system and all ASE – as part of this study. Early in the study it became evident that shuttle/OMV performance would limit the altitudes at which baseline SIRTf servicing could be performed. The baseline assumptions were reexamined to define a "lightweight" set. A total of 2000 kg were cut from the SIRTf spacecraft bus (2010 kg versus 4010 kg). The dry weight of the cryogen replenishment system was cut in half (1250 kg versus 2500 kg for a 1250-kg cryogen capacity). The 2500-kg estimate was based on an empirical 2:1 ratio of dewar to cryogen mass. We did not consider whether this could be made smaller than 1:1, which provided the 1250-kg lightweight estimate.

The ASE estimates used were 1500-kg baseline and 1000-kg lightweight. These are conservative estimates where the assumption was that SIRTf would be cantilevered from Multimission Modular Spacecraft (MMS) FSS cradle set or installed in a SIRTf cradle (or cradles). The ASE on the shuttle for the cryogen replenishment system includes cradle(s) to carry the CRS and associated equipment – fill lines, couplings, controllers, and interfaces for shuttle aft deck command and monitor panel. ASE also incorporates the mechanisms for berthing SIRTf, as well as the facilities to accommodate astronauts in their role in servicing. Table 5-1 shows the comparative values for the baseline and lightweight configurations.

5.2 SIRTf REPLENISHMENT MISSION OPTIONS AND PERFORMANCE

Figure 5-1 describes seven optional scenarios that might be used in performance of the SIRTf Instrument Changeout and Cryogen Replenishment Mission. Although not exhaustive, they encompass all functions likely to be required.

The pictorials present a visual representation of the defined missions. Both free-flying and platform-mounted SIRTfs are included. The manifest columns identify the major elements involved in each scenario and their total mass in kilograms.

To limit the scope of the study, three reference missions were selected for more analysis of operations. The goal was to choose those that best fit the total potential range of functions that could be involved in all the scenarios. From these considerations, scenarios I, V, and VII were selected and are subsequently referred to as Reference Mission (RM) 1, 2, and 3.

RM1 uses the STS orbiter capability of direct injection to the free-flying SIRTf for servicing in the orbiter bay. RM2 employs the OMV to retrieve the free-flying SIRTf for servicing at the space station. RM3 employs an

Table 5-1 MASS ASSUMPTIONS

Item	Mass (kg)	
	Baseline	Lightweight
SIRTF - Wet	7250	5250
ASE*: Shuttle for SIRTF	1500	1000
ASE: OMV for SIRTF	100	100
Cryogen Replenishment System (CRS) Dry	2500	1250
CRS Cryogen	1250	1250
ASE: Shuttle for CRS	1250	1000
ASE: OMV for CRS	250	250
OMV - Wet	4800	4800
ASE: Shuttle for OMV	1200	600

*ASE = Airborne Support Equipment

integrated OMV, cryogen supply tank, and robotics module to perform SIRTF servicing remote from the space station.

Figure 5-2, depicting shuttle performance at 98-deg inclination and Fig. 5-3, depicting shuttle performance at 28.45-deg inclination, were both taken from the SIRTF Phase A Free Flyer System Concept Description. These data were used in conjunction with OMV performance estimates and mass assumptions to estimate altitude capabilities for both SIRTF deployment and SIRTF servicing.

For sun-synchronous orbits, where shuttle and OMV are employed, the assumption was that shuttle would achieve a sun-synchronous parking orbit and that OMV would then provide both an altitude increment and the plane change required for sun synchronism in the higher orbit. As an example, the sun-synchronous inclination at 200 km is 96.327-deg. If shuttle is parked at this altitude while OMV deploys a payload at 600 km where the sun-synchronous inclination is 97.787-deg, the OMV capability is reduced by the requirement to provide a 1.46-deg plane change. Values from Fig. 5-4 were used to assess performance for both deployment and servicing missions.

The OMV performance shown in Fig. 5-5 was plotted from data supplied by MSFC for the current 3930 lbm (1783 kg) dry OMV with 6556 lbm (2974 kg) usable propellants with a 285-s specific impulse.

"Delivery", "Retrieval", and "Round Trip" are two-leg operations, where the payload is carried on only one leg (delivery or retrieval), or on both legs of the round trip. "Retrieve and Deploy" is a four-leg operation where the OMV

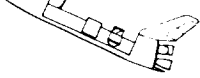
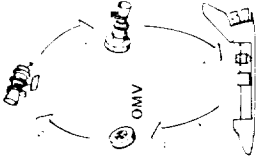
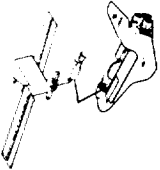
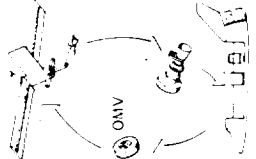
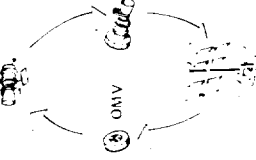
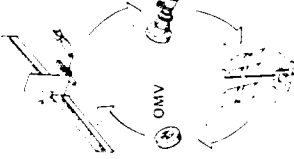

RESUPPLY MISSION ELEMENTS							
SCENARIO	I	II	III	IV	V	VI	VII
SELECTED REF	RM1 @ 28.5°				RM2		RM3
SIRTf CONFIG	FREE FLYER	FREE FLYER	PLATFORM	PLATFORM	FREE FLYER	PLATFORM	PLATFORM
MANIFEST	LAUNCH	LAUNCH	LAUNCH	LAUNCH	UP	UP	UP
SIRTf	7,250	7,250	N.A	N.A	7,250	5,250	DN
SIRTf ASE	1,500	1,500			250	250	4,750
CRYO RESUPP DRY							250
CRYO	2,500	2,500	2,500	2,500			2,500
CRYO ASE	1,250	1,250	1,250	1,250			1,250
OMV WET	1,250	1,250	1,250	1,250			250
OMV ASE SSO	4,800	4,800	4,800	4,800			
OMV/SIRTf I.F	1,200	1,200	1,200	1,200			
TOTAL	8,750	14,850	5,000	11,100	7,500	5,500	4,000
	RESUPPLY	RESUPPLY	RESUPPLY	RESUPPLY	DN	DN	DN
	5,000	11,100	5,000	11,100	7,000	5,000	2,750

Fig. 5-1 SIRTf Replenishment Mission Options and Reference Selection

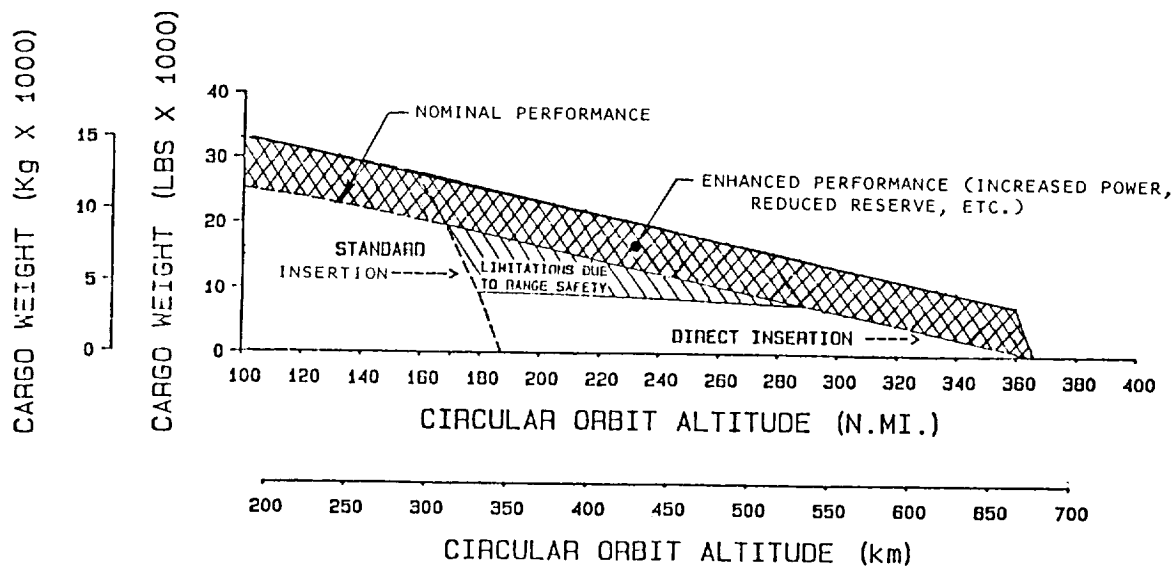


Fig. 5-2 Cargo Weight Versus Circular Orbit Altitude (98-deg Inclination)

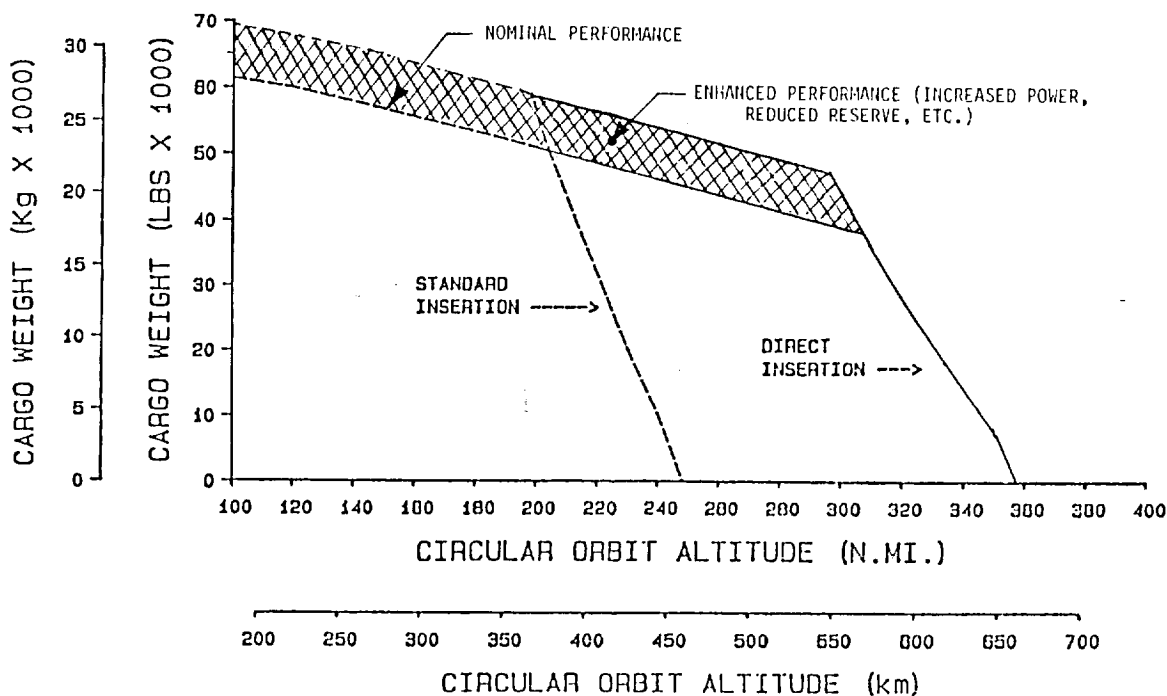


Fig. 5-3 Cargo Weight Versus Circular Orbit Altitude (28.45-deg Inclination)

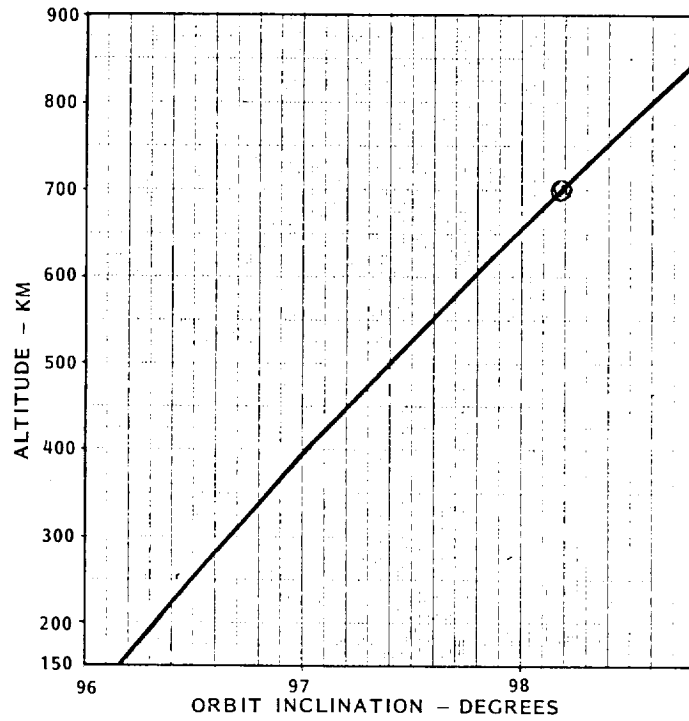


Fig. 5-4 Sun-Synchronous Inclination Versus Altitude

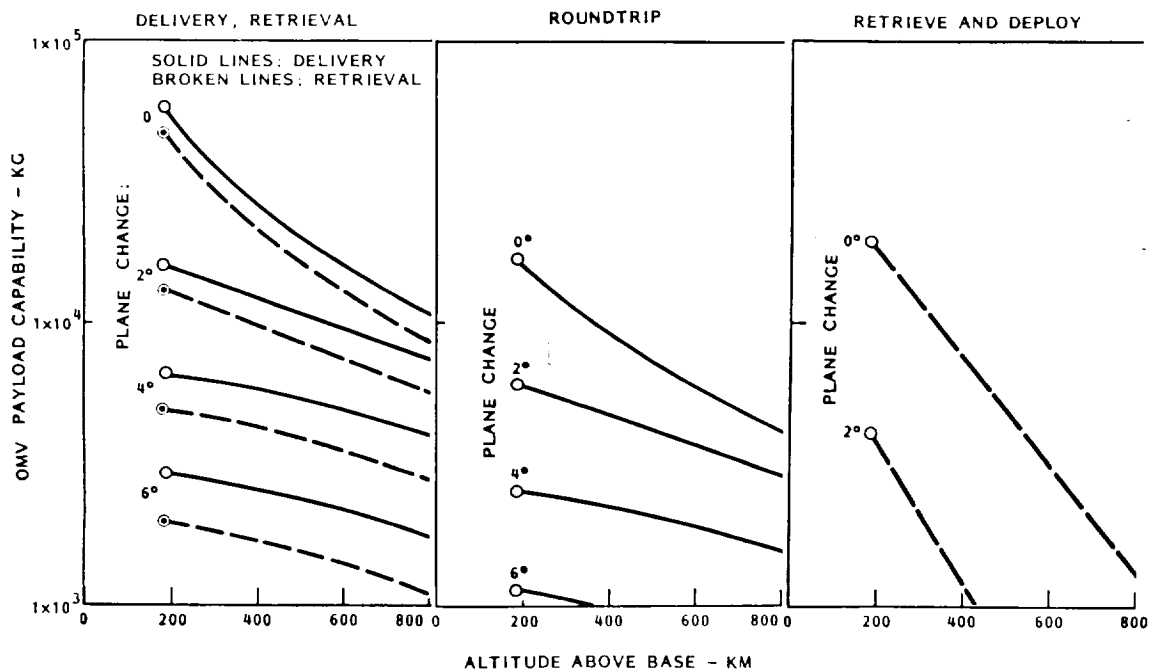


Fig. 5-5 OMV Performance

performs a rendezvous with the payload in the payload operational orbit (leg 1), returns the payload to the service base (leg 2), without refueling deploys the payload back to the operational orbit (leg 3), and finally returns to the service base (leg 4).

Figure 5-6 shows the orbit altitudes achievable for baseline and lightweight SIRTf and ASE masses using the shuttle and OMV performance curves for sun-synchronous orbits. Both launch (initial deployment) and resupply cases are shown. For Scenario I, the initial deployment to 315 to 350 km using shuttle only is the limiting case, while in Scenarios II, III, IV, the resupply capability using both shuttle and OMV is the limiting case. The baseline SIRTf masses always require a zero margin shuttle for deployment. Otherwise, a scenario must be devised in which the shuttle carries only the SIRTf and meets the OMV on orbit.

Nodal regression, or rotation of the orbit plane about the earth's axis of rotation, is a function of both inclination and orbit period (altitude). Nodal regression causes the satellite orbit planes having different altitudes, but the same inclination, to drift apart at what is termed the "differential orbit regression rate". Because of the inclination dependency, the nodal regression rates are significantly higher for low-inclination orbits than for those at high inclination. Figure 5-7 illustrates this phenomenon.

The differential orbit regression rate between a fixed-altitude base (orbiter or space station) and a fixed-altitude satellite (e.g., space platform) is of concern, since this will determine when the orbits become coplanar and consequently the periodicity of feasible satellite revisits from the base. It also determines the duration of servicing allowed by the OMV plane change capability (Fig. 5-8).

The differential regression rates shown in Fig. 5-8 were used to generate the nodal coincidence intervals presented in Fig. 5-9. These data must be considered in selecting SIRTf operational altitudes and mean mission duration (reliability) requirements of the SIRTf design for the scenarios in which the space station is employed. The accessibility of SIRTf for servicing is not a problem with the shuttle, since the shuttle can be launched at any time (any day) to achieve nodal coincidence with the SIRTf.

The retrieval window for a space station-based OMV and free-flying SIRTf (Scenario V) depends on the differential regression rates and the OMV plane change capability. If the window is considered to open when the SIRTf orbit plane reaches Δi before the space station orbit plane, and close when the SIRTf orbit plane is Δi past the space station orbit plane, then the window length is $2 \Delta i / \Delta ORR$, with values shown in Table 5-2.

Scenarios IV, VI, and VII (Fig. 5-1) are cases in which there is a fixed service base altitude (shuttle or space station) and a fixed SIRTf (space platform) altitude. The OMV performance carrying the particular payload required for a given scenario determines how much time can be allocated to

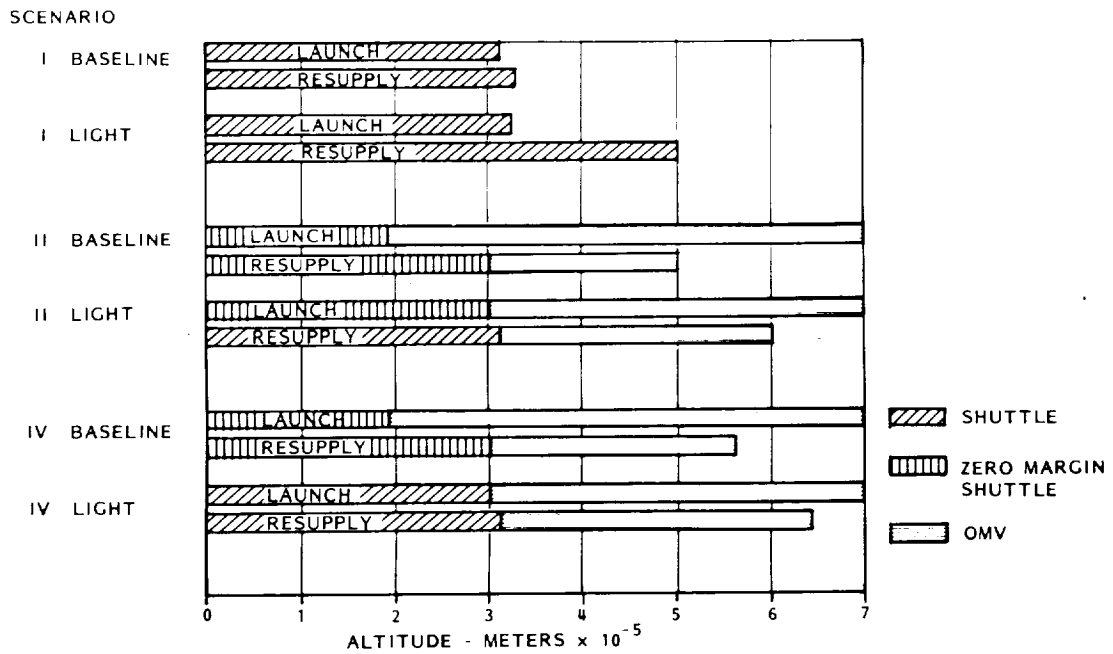


Fig. 5-6 Sun-Synchronous Orbit Altitude Capabilities

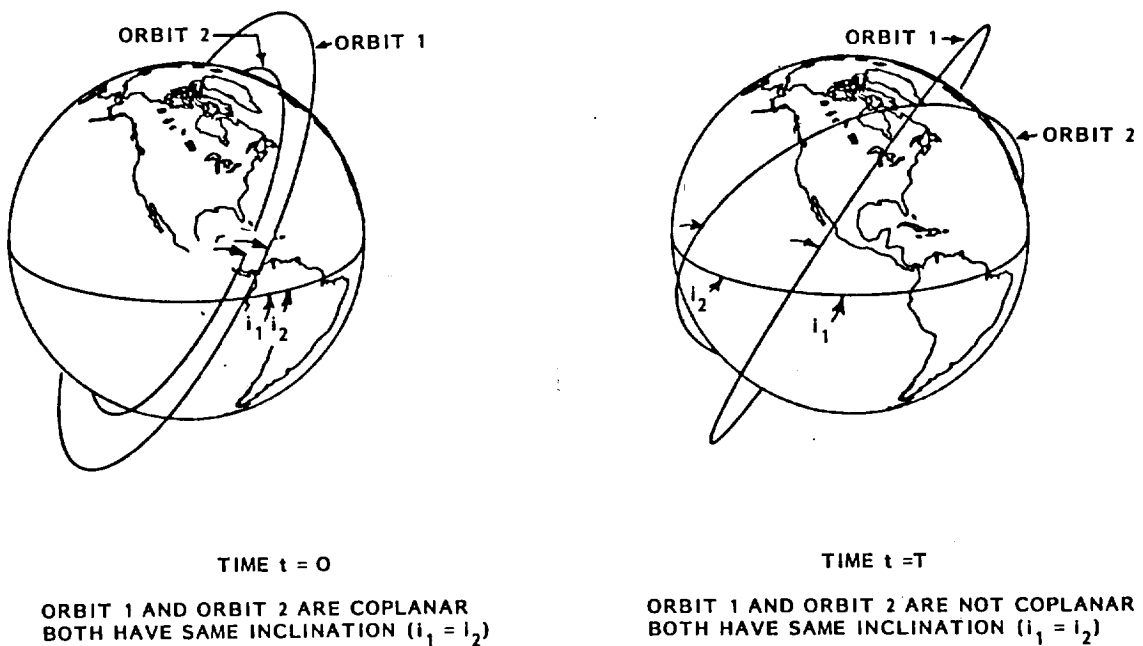


Fig. 5-7 Effect of Nodal Drift of Circular Orbits at Same Inclination but With Different Altitudes

DIFFERENTIAL ORBIT REGRESSION RATE (SATELLITE RATE-BASE RATE) IS POSITIVE IF SATELLITE IS HIGHER THAN BASE (SOLID LINES) AND NEGATIVE IF SATELLITE IS LOWER THAN BASE (DASHED LINES)

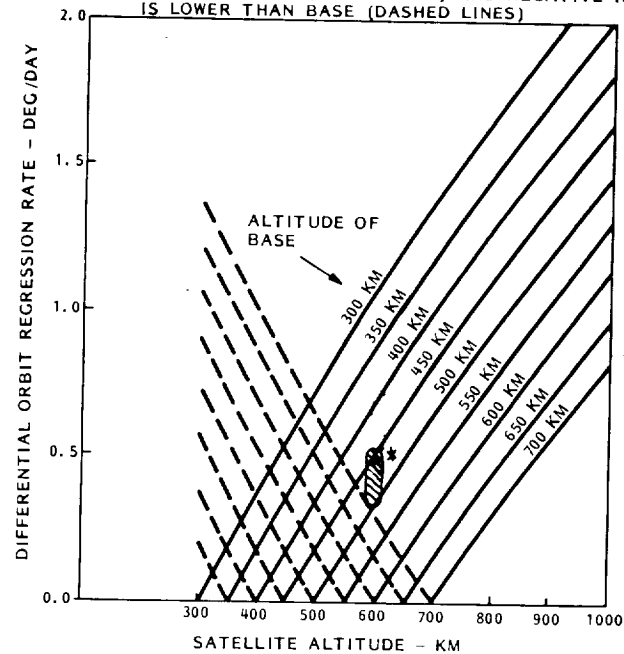


Fig. 5-8 28.45-deg Orbits' Orbit Regression Rate Differences Between Fixed-Altitude Base and Satellite at Various Altitudes

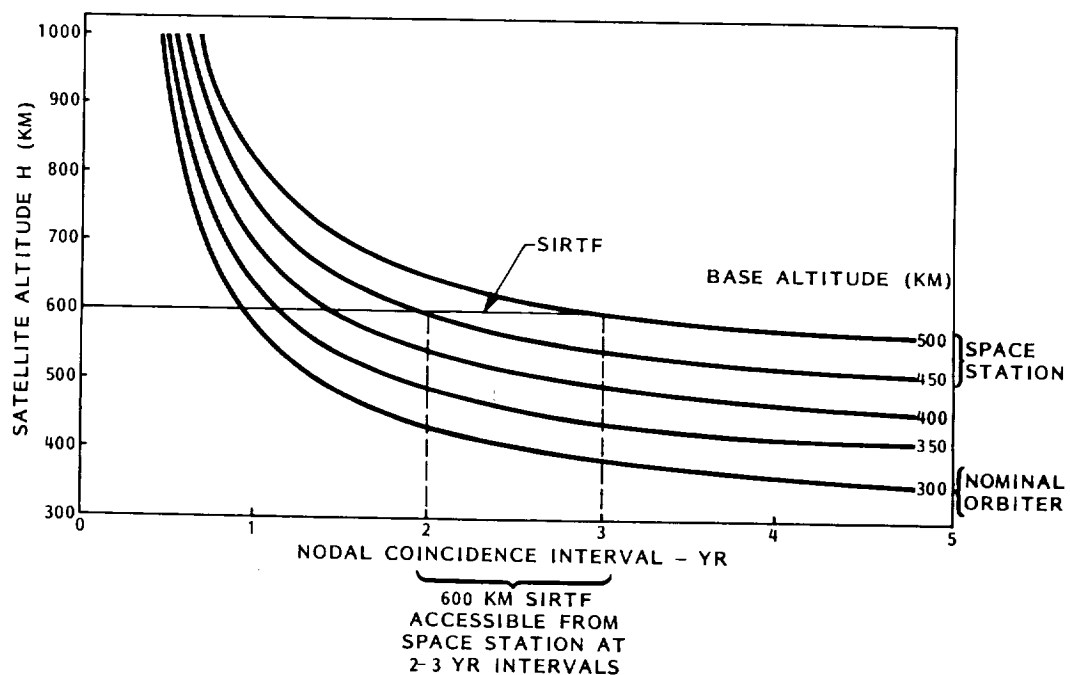


Fig. 5-9 28.45-deg Orbits' Interval Between Nodal Coincidences as Function of Altitude

Table 5-2 SIRTf FREE-FLYER RECOVERY WINDOW FROM SPACE STATION

Base (SS) Altitude (km)	SIRTf FF Altitude (km)	Δ ORR deg/day	Δi (deg)		Window (Days)	
			Baseline Weight	Lightweight	Baseline Weight	Lightweight
450	900	1.38	3.1	4.1	4.5	5.9
500		1.21	3.2	4.2	5.1	6.9
450	800	1.11	3.3	4.3	5.9	7.7
500		0.94	3.4	4.4	7.2	9.4
450	700	0.81	3.5	4.4	8.6	10.9
500		0.64	3.6	4.5	11.3	14.1
450	600	0.50	3.6	4.6	14.4	18.4
500		0.33	3.7	4.6	22.4	27.9

performing the service. The servicing duration limits shown in Fig. 5-10 are equal to twice the OMV plane change capability divided by the differential orbit regression rate.

Scenario VII is severely constrained because the OMV performance is based on the "round-trip" case, while refueling is assumed in Scenario VI, permitting the OMV "delivery/retrieval" performance to be used. Figure 5-11 repeats the scenario definitions and indicates the altitude and plane change capabilities for each scenario.

5.3 SIRTf RELIABILITY AND AVAILABILITY CONSIDERATIONS

Figure 5-12 defines the various terms used in evaluating the impact of the various scenarios on the overall SIRTf reliability. Accessibility is defined for the space station service base as the time for the SIRTf to reach coplanarity with the space station. For the shuttle service scenario the accessibility is limited only by how fast a shuttle mission can be arranged (estimated here at 90 to 180 days).

Availability is defined as the ratio of the up time to the total time. For the space station the "total" time is the accessibility interval. For the shuttle it is the up time plus the shuttle access time. Reliability is the simple exponential probability of success which is used to relate the accessibility and availability to the desired parameter, mean time to failure (MTTF). The timeline shown indicates the relations that exist in the two cases.

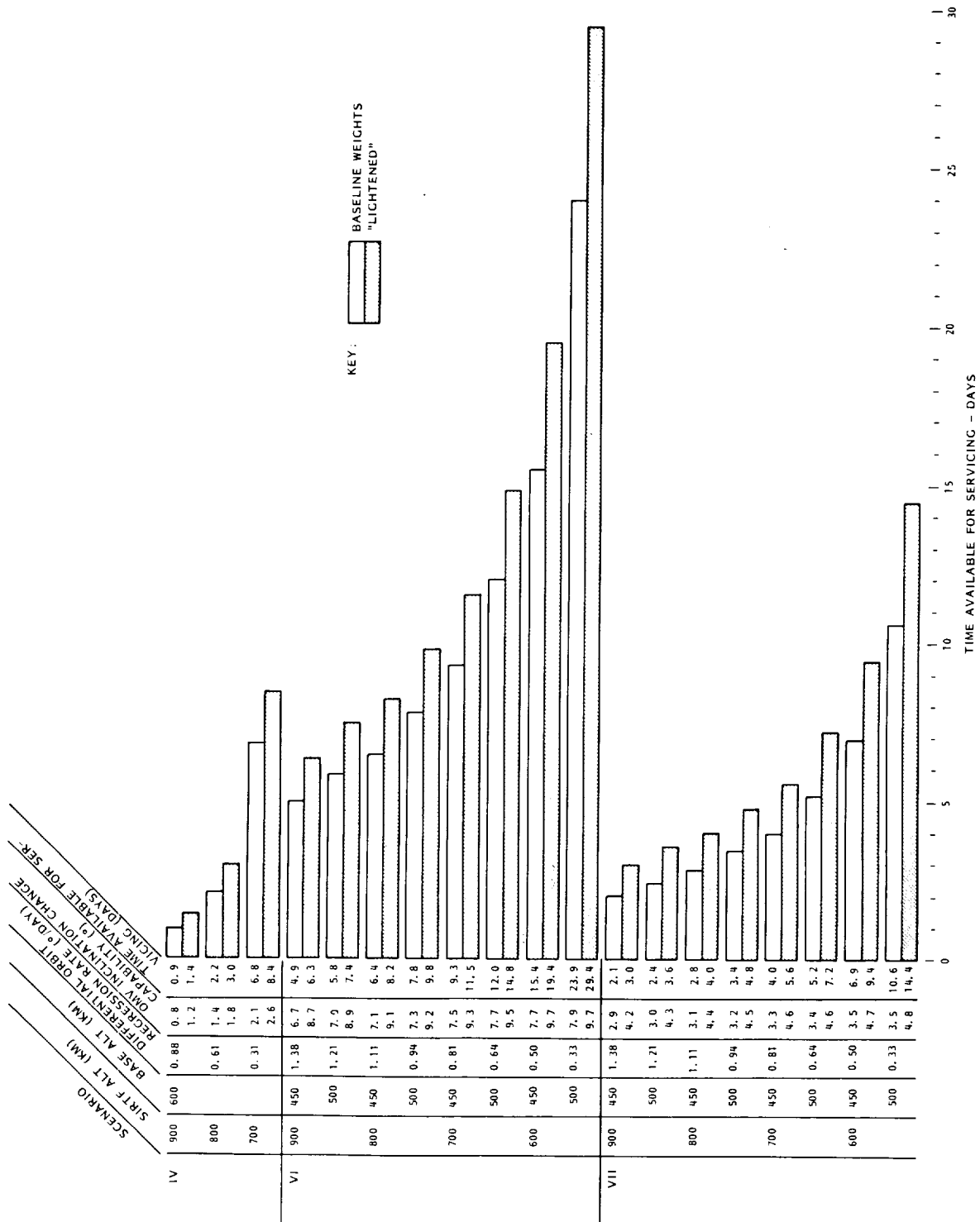
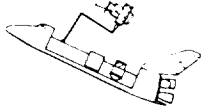
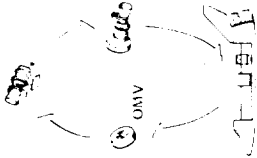

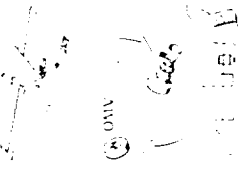
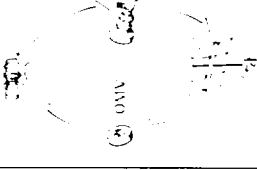
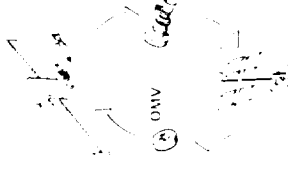



Fig. 5-10 Servicing Duration Limits for 28.5-deg Replenishment Scenarios

RESUPPLY MISSION ELEMENTS							
SCENARIO	I	II	III	IV	V	VI	VII
SELECTED REF	RM1 @ 28.5°				RM2		RM3
SIRTF CONFIG	FREE FLYER	FREE FLYER	PLATFORM	PLATFORM	FREE FLYER	PLATFORM	PLATFORM
	LAUNCH	RESUPPLY	LAUNCH	RESUPPLY	LAUNCH	RESUPPLY	LAUNCH
SHUTTLE	313	330	N/A	302*	N/A	302*	450
OMV		570	200	200	N/A	260	250
TOTAL	313	330	502	502	502	562	700
SHUTTLE	617	640	N/A	601	N/A	601	450
OMV		120**	100**	100	N/A	100	250
TOTAL	617	700	701	701	701	701	700
OMV Δi		3.8**	1°**	1°	N/A	1°	1.6°
INCLINATION	28.45°						
SYNCHRONOUS SUN							
SS ALT						450	
OMV						250	
TOTAL						700	
OMV Δi						3°	

* Zero margin shuttle

** If scenario II is selected to provide a SIRTF operational altitude of 900 km at 28.45 deg, the OMV provides a 320-km ΔH with a 3.4-deg Δi for launch and a 299-km ΔH with 0.6-deg Δi margin for the resupply mission. Margins will improve as the conservative masses in the Fig. 5-2 manifests are reduced.

Fig. 5-11 SIRTF Replenishment Mission Altitude Capabilities

• DEFINITIONS

ACCESSIBILITY: INTERVALS AT WHICH SIRTf CAN BE REACHED FOR SERVICING

- DEFINED BY ORBIT GEOMETRY FOR SPACE STATION $T_{SS} = 1.2 - 3$ YEARS

- DEFINED BY "ON-DEMAND" AVAILABILITY OF THE SHUTTLE

$$\Delta T_{SO} = 90 - 180 \text{ DAYS}$$

AVAILABILITY: RATIO OF UPTIME TO TOTAL TIME

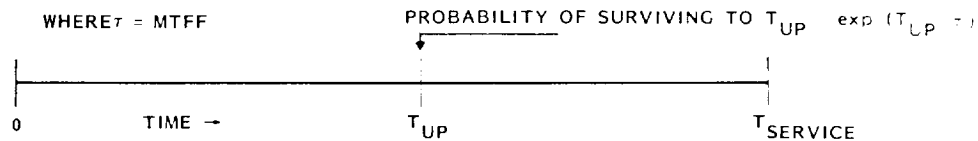
- $A_{SS} = T_{UP}/T_{SS}$ FOR SPACE STATION

- $A_{SO} = T_{UP}/(T_{UP} + \Delta T_{SO})$ FOR SHUTTLE

RELIABILITY: SIMPLE EXPONENTIAL MODEL FOR PROBABILITY OF SUCCESS

$$- R = P_S = \exp(-t/\tau)$$

WHERE $\tau = \text{MTTF}$



$$T_{UP} = \Delta T_{SO} * A_{SO} / (1 - A_{SO}) \text{ ORBITER}$$

$$= T_{SS} * A_{SS} \text{ SPACE STATION}$$

$$T_S = T_{UP} + \Delta T_{SO} \text{ ORBITER}$$

$$= T_{SS} \text{ SPACE STATION}$$

Fig. 5-12 SIRTf Reliability Considerations

In the case of servicing from the shuttle, required minimum MTTF is computed at selected levels of availability and probability of success. Setting high values on availability and/or probability of success leads to multiyear MTTF. This is placed into perspective by noting that the current estimate for the Space Telescope MTTF is 0.54 year (reference "Space Telescope Reliability/Maintainability Data Base for Inputs to MSFC Maintainability Model," ST/MR 24, 30 Nov 1984). Space Telescope was not designed with a consistent goal of maximizing the MTTF; however, the required value of the SIRTf MTTF computed here indicates the importance of early establishment of such a goal.

Figure 5-13 shows the required SIRTf MTTF given various values for availability and probability of success. The MTTF is computed in Fig. 5-14 for the space station servicing case. The selected probabilities of success and availabilities are 0.9, 0.8, and 0.7. The MTTF is listed for each of the combined options and for the range of access times which are functions of the orbit parameters. The conclusions of Fig. 5-13 are reinforced by the higher reliabilities (higher MTTFs) required in this case. From a SIRTf design standpoint, replenishment at the orbiter is preferred to that at the space station. It is also noted that for the space station case the shorter revisit times are a definite advantage. This means that the largest separation in orbit altitude should be selected to minimize the accessibility time span.

Another option might be to make the SIRTf co-orbital with the station and thereby make it continuously accessible by OMV.

$$T_{UP} = \Delta T_{SO} * A_{SO} / (1 - A_{SO})$$

PROBABILITY THAT THE SIRTf DOES NOT FAIL PRIOR TO T_{UP}

$$P_{S0} = \exp (-T_{UP} / \tau)$$

THUS: REQUIRED MTTf (τ) IS GIVEN BY: $-T_{UP} / \ln P_{S0}$

FOR $T_{SO} = 90$ DAYS = 1/4 YR

SELECTED AVAILABILITY	SELECTED P_S	T_{UP} (YR)	REQUIRED MTTF (YR)
0.9	0.9	1.75	16.6
	0.8		7.8
	0.7		4.9
0.8	0.9	1.0	9.5
	0.8		4.5
	0.7		2.8
0.7	0.9	0.58	5.5
	0.8		2.6
	0.7		1.6

Fig. 5-13 Required SIRTf Reliability for Servicing by Shuttle

$$MTTF (\tau) = -T_{SS} / \ln P_S$$

$$T_{UP} = T_{SS} * A_{SS}$$

SELECTED AVAILABILITY	SELECTED P_S	SERVICE INTERVAL (T_{SS}) (YEAR)							
		3		2		1.6		1.2	
		T_{UP}	MTTF	T_{UP}	MTTF	T_{UP}	MTTF	T_{UP}	MTTF
0.9	0.9	2.7	25.6	1.8	17.1	1.4	13.7	1.1	10.3
	0.8		12.1		8.1		6.5		4.8
	0.7		7.6		5.0		4.0		3.0
0.8	0.9	2.4	22.8	1.6	15.2	1.3	12.1	1.0	9.1
	0.8		10.8		7.2		5.7		4.3
	0.7		6.7		4.5		3.6		2.7
0.7	0.9	2.1	19.9	1.4	13.3	1.1	10.6	0.8	8.0
	0.8		9.4		6.3		5.0		3.8
	0.7		5.9		3.9		3.1		2.4
ALTITUDE CASES		SIRTf (KM)		600		600		700	
		SS (KM)		500		450		500	
								700	
								450	

Fig. 5-14 Required SIRTf Reliability for Servicing at Space Station

5.4 REFERENCE MISSION CONCEPTS AND TIMELINES

Reference mission 1 involves the orbiter rendezvous and capture of SIRTf. The steps in performing this mission are shown in Fig. 5-15. This concept has the supply dewar and SIRTf mounting interface integrated to maximize the utility of the structure for on-orbit servicing. It is assumed that the antennas and solar arrays have been retracted for servicing. The aft end of the SIRTf is mated to the rotatable table. This facilitates ORU and instrument changeout from one location which minimizes the time and complexity of the EVA. The instrument checkout is done while the SIRTf is warm and may occupy several separate EVA operations. The cryogen transfer line is attached at the end of the first EVA. The cryogen operations are controlled and monitored by a mission specialist at the payload station on the orbiter aft flight deck. After cryogen replenishment and checkout, the second EVA will disconnect the umbilical and cryogen transfer lines. The SIRTf is separated from the cryogen replenishment system by use of the RMS and redeployed.

Table 5-3 presents estimates of how the replenishment missions would fit into the overall space shuttle programming. It has been determined that access to

Table 5-3 REPLENISHMENT MISSION OVERALL TIME SPANS

Mission Time (Days)		Planned Activity
Shuttle Replenishment	Space Station Replenishment	
0	0	Start charging Cryogen Replenishment Dewar (CRD)
5	5	CRD filled
10	10	Load CRD on orbiter
13	13	Top off CRD
15	15	Launch space shuttle
16-17	16-17	Shuttle rendezvous and dock with a. SIRTf, b. space station
	18	CRD off-loaded to space station
	21	OMV deployed to retrieve SIRTf (access window opens)
17	22	Start SIRTf replenishment
22	27	Complete SIRTf cryogen replenishment
22	28	SIRTf redeployed

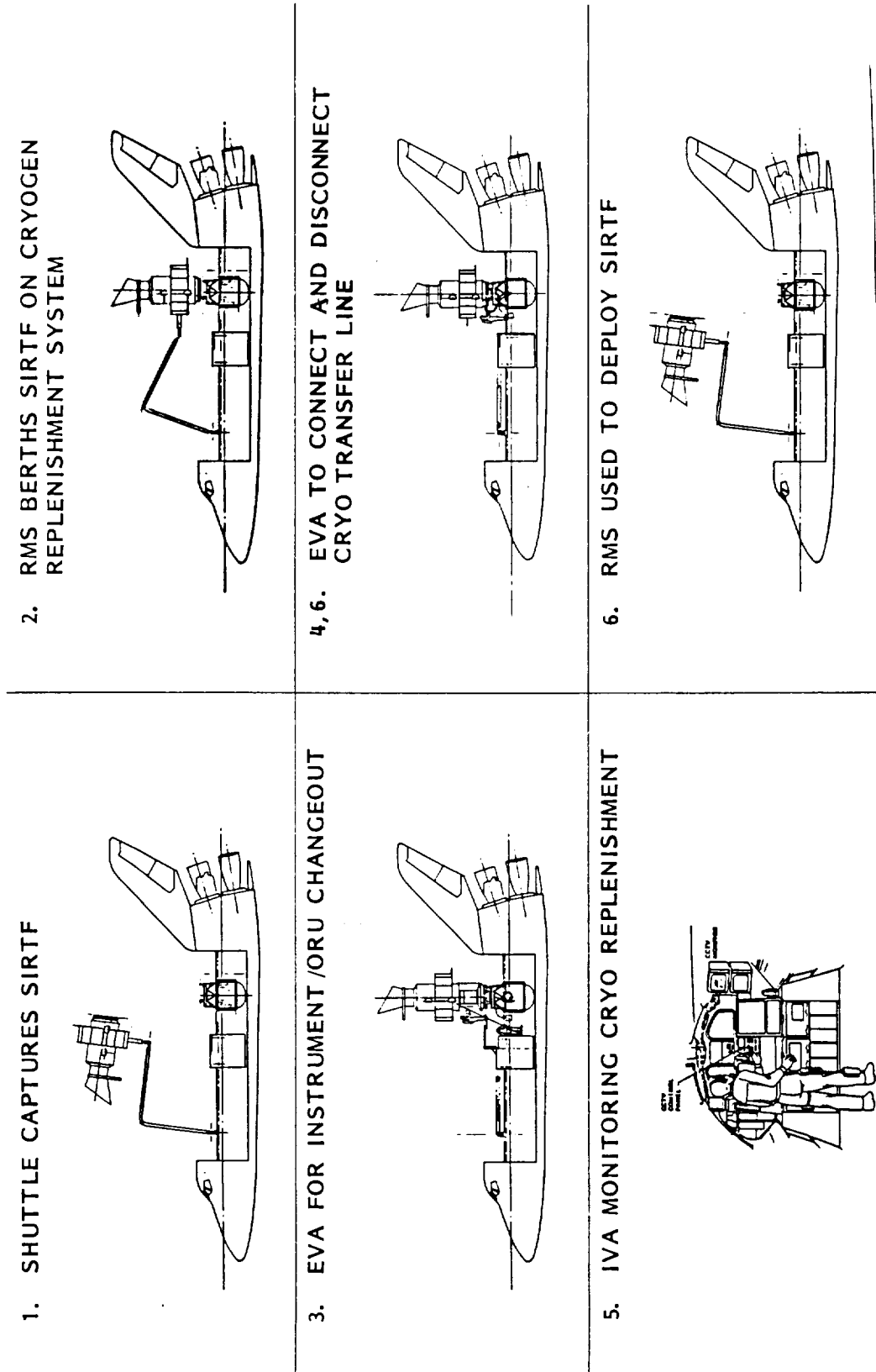


Fig. 5-15 Reference Mission 1 Concept

a payload [the Cryogen Replenishment Dewar (CRD)] can be made two days before launch for top-off of the cryogen. The shuttle orbiter which performs the replenishment mission by itself or aided by an OMV can complete the replenishment in approximately 22 days from the start of filling the CRD. In the case of the space station, the CRD is offloaded at the station and status determined prior to dispatch of the OMV to recover the SIRTF. Sufficient delays must be built into the plan to ensure that a full dewar is in place prior to achieving orbit coplanarity which enables the recovery of the SIRTF. It is estimated that a span as short as 27 days from CRD fill start is feasible for the space station case. Table 5-4 shows the overall timeline for Reference Mission 1 - the shuttle-based replenishment mission. The 14-day mission (12 days plus 2 contingency) with a 5-person crew (commander, pilot, and three mission specialists) has a 465- to 687-kg charge levied as payload weight, depending upon its classification as either a dedicated flight or a deployable flight.

The 14 days might be reduced to 12 (10 + 2) if cryogen replenishment can be started at Day 3.5, with completion at Day 7.5, and the events show for Days 9 through 12 rescheduled for Days 7 through 10.

Figures 5-16 and 5-17 show the Space Telescope Orbital Maintenance Mission for Flight Days 1 and 2. The first 2 days of a carefully considered timeline for a Space Telescope maintenance mission are shown to illustrate the functions and time required between shuttle launch and the first EVA. Milestones are as follows:

Mission Elapsed Time (day:h:min)	Event
00:00	Launch
05:45	Circularize in Standoff Orbit
06:00	Start Meal/Sleep/Meal
18:00	Start Rendezvous/Stationkeeping
1:00:00	Start Retrieval Sequence
1:03:30	ST Captured by RMS
1:05:00	Retrieval Complete, ST on Orbiter Power
1:05:30	Start Meal/Sleep/Meal
1:18:00	Start EVA Prep
1:19:30	Start EVA

In Reference Mission 1, the SIRTF will be serviced by a dedicated shuttle mission. The baseline replenishment mission is conducted at 400- to 600-km altitude, 28.5-deg inclination. The SIRTF will be captured by the orbiter's RMS and docked to the cryogen replenishment system. Two EVA crew members will assist on the docking and setup, and perform the ORU changeout and cryogen

Table 5-4 REFERENCE MISSION 1 DURATION/TIMELINE

Shuttle-Based SIRTF Replenishment Mission	
Flight Day 1	Launch/on-orbit preparation
Flight Day 2	Rendezvous and retrieve SIRTF
Flight Day 3	EVA No. 1: ORU changeout, cryogen replenishment preparation
Flight Days 4-8*	SIRTF cool-down and cryogen replenishment
Flight Day 9	EVA: disconnect and secure cryogen transfer equipment
Flight Day 10	Deploy SIRTF
Flight Day 11	Orbiter FCS checkout, cabin configuration, and thermal conditioning
Flight Day 12	Deorbit/landing
Plus 2 days for weather contingency	

*Actual time span TBD from SIRTF cool-down and fill time

transfer line hookup. Then the EVA crew members will return to the orbiter airlock while the SIRTF system checkout and cryogen replenishment operations are carried out under the control of the mission specialist on the aft flight deck.

The two EVA crew members disconnect the cryogen transfer line after it has been cleared and vented. All tools and EVA fixtures are stowed in the ORU spare carrier. The tool caddy is closed out, and the RMS is attached to SIRTF for deployment after the astronauts reenter the orbiter. This timeline is illustrated in Fig. 5-18.

In Reference Mission 2 the SIRTF is brought to the space station by the OMV. It is maneuvered to the satellite service bay and captured by the MRMs. The OMV is demated and returned to its storage/refueling station. The instrument and ORU changeout is accomplished. After all systems have been checked, the cryogen dewar is brought near the SIRTF using a station-supplied transport trolley. The cryogen transfer line is manually connected. After the cryogen replenishment has been accomplished, the cryogen transfer line is manually disconnected along with the signal/power umbilical. The SIRTF is remated to the OMV by the MRMS. The combined vehicle is then released for return to operational orbit. Figure 5-19 illustrates the Reference Mission 2 scenario.

5-19

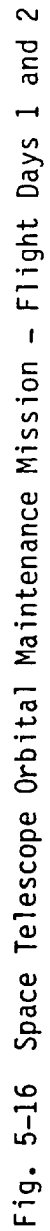


Fig. 5-16 Space Telescope Orbital Maintenance Mission - Flight Days 1 and 2

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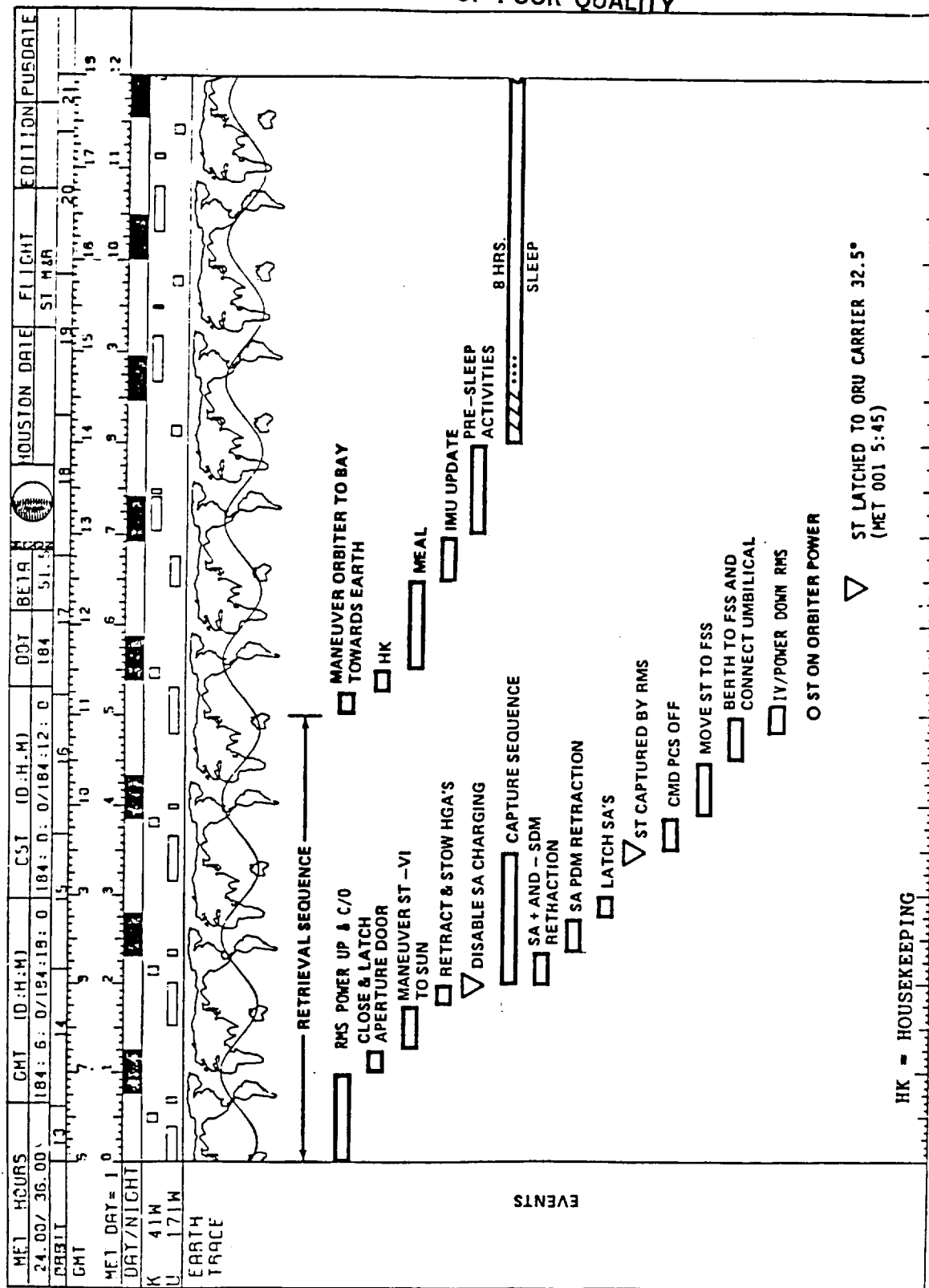
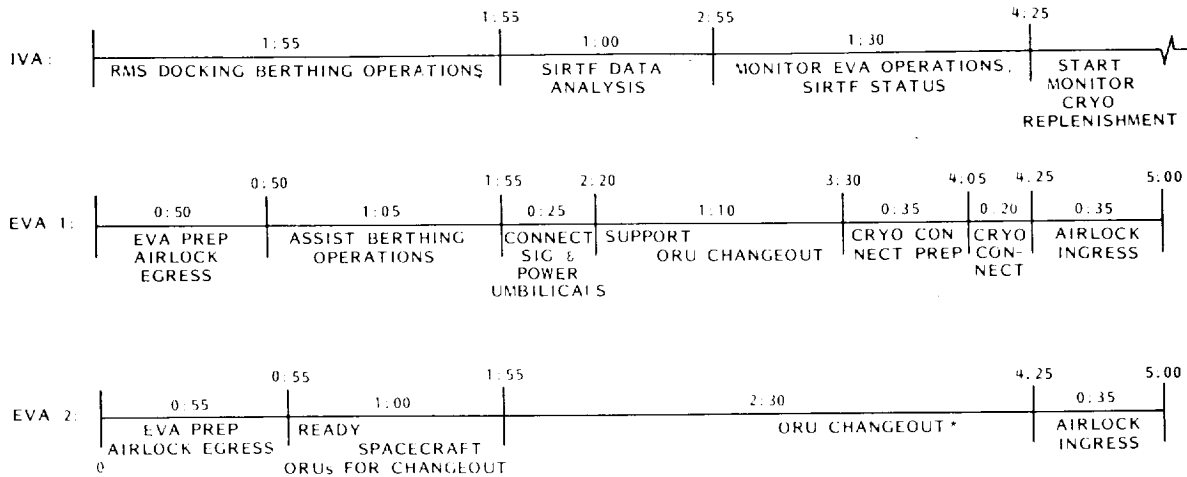


Fig. 5-17 Space Telescope Orbital Maintenance Mission - Flight Day 2

CRYOGEN REPLENISHMENT SYSTEM CONNECT



*MAY REQUIRE SECOND EVA DEPENDING ON EXTENT OF EQUIPMENT CHANGEOUT.

DISCONNECT CRYOGEN REPLENISHMENT SYSTEM

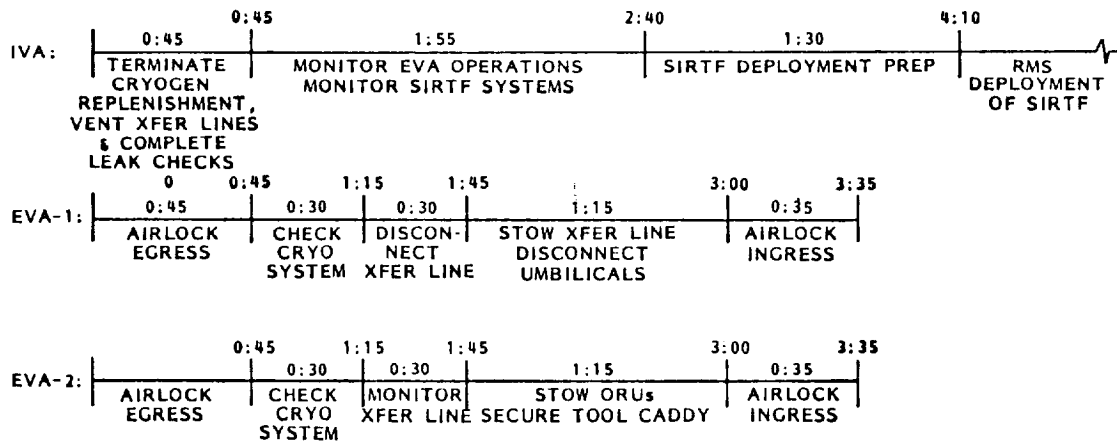


Fig. 5-18 IVA/EVA Timeline for Reference Mission 1

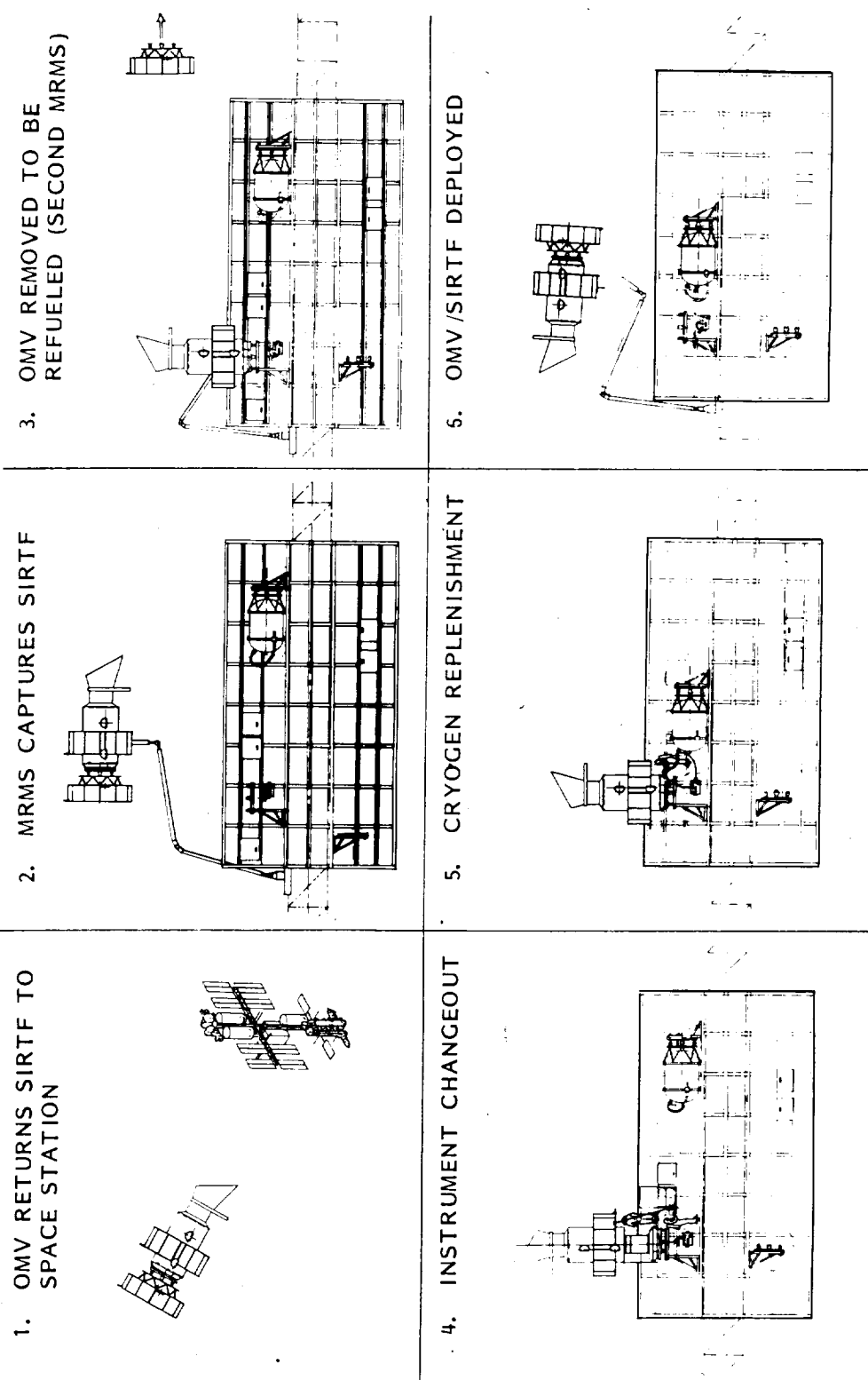


Fig. 5-19 Reference Mission 2 Concept

The overall timeline for Reference Mission 2 includes approximately 16 h on Day 1 and Day 3 for each of the OMV transits from space station to the SIRTF free flyer and return. As in Reference Mission 1, this time might be shortened by allowing only 4 days for cryogen replenishment – from Day 4.5 to Day 8.5.

- Day 1 - OMV depart space station, rendezvous, and dock with SIRTF
- Day 2 - Check out SIRTF, prep for return to station
- Day 3 - Rendezvous and dock at space station
- Day 4 - EVA demate SIRTF and OMV. Berth SIRTF in satellite servicing bay. (OMV is moved to OMV servicing/refueling station.) ORU replacement. Prep for cryogen replenishment
- Day 5-9 - Cryogen replenishment
- Day 10 - EVA disconnect cryogen supply. Mate SIRTF and OMV. OMV depart space station
- Day 11 - OMV check out and deploy SIRTF. OMV return to space station

The IVA/EVA timeline for Reference Mission 2 is shown in Fig. 5-20. The two space station EVA crew members direct the MRMs docking of the SIRTF to the satellite service bay. The power/signal umbilical is attached, and ORU changeout tasks are performed. The final task before returning to the airlock is to connect the cryogen transfer line.

The EVA crew members complete the post-cryogen-replenishment tasks by disconnecting the electrical/data umbilical and cryogen transfer line. The EVA crew members also assist in mating the OMV to the SIRTF utilizing the mobile RMS.

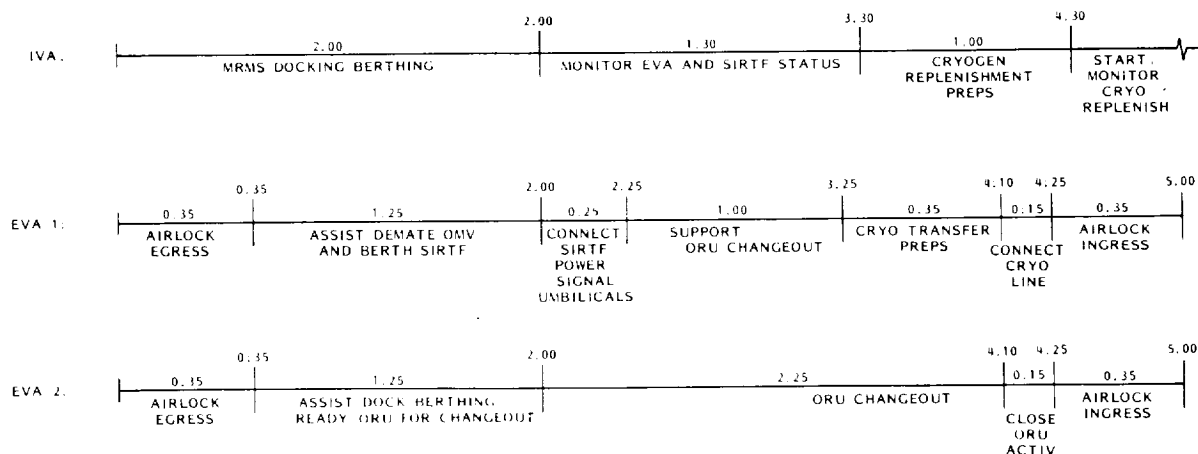
In Reference Mission 3 the SIRTF is replenished on-orbit by a dedicated remote servicer mated to an OMV. Fig. 5-21 shows the servicer being mated to the OMV at the space station. The OMV transfers the servicer to the SIRTF platform orbit where it meets and docks with the platform. When the cryogen replenishment is completed, the servicer/OMV will disengage from the platform and return to the space station.

The Reference Mission 3 timeline shown below indicates an 8-day span (Days 2 through 9) between OMV departure from and return to the space station.

- Day 1 - EVA prep OMV/SIRTF servicer
- Day 2 - Rendezvous, prep for replenishment
- Day 3 - ORU changeout, SIRTF checkout
- Day 4-8 - Cryogen replenishment
- Day 9 - Rendezvous and dock at space station
- Day 10 - EVA demate, prep, and store OMV and SIRTF servicer

In order to perform this mission, the SIRTF altitude relative to the space station must be carefully selected to meet the servicing mission duration constraints imposed by nodal drift shown in Fig. 5-8.

CONNECT CRYOGEN REPLENISHMENT SYSTEM



DISCONNECT CRYOGEN REPLENISHMENT SYSTEM

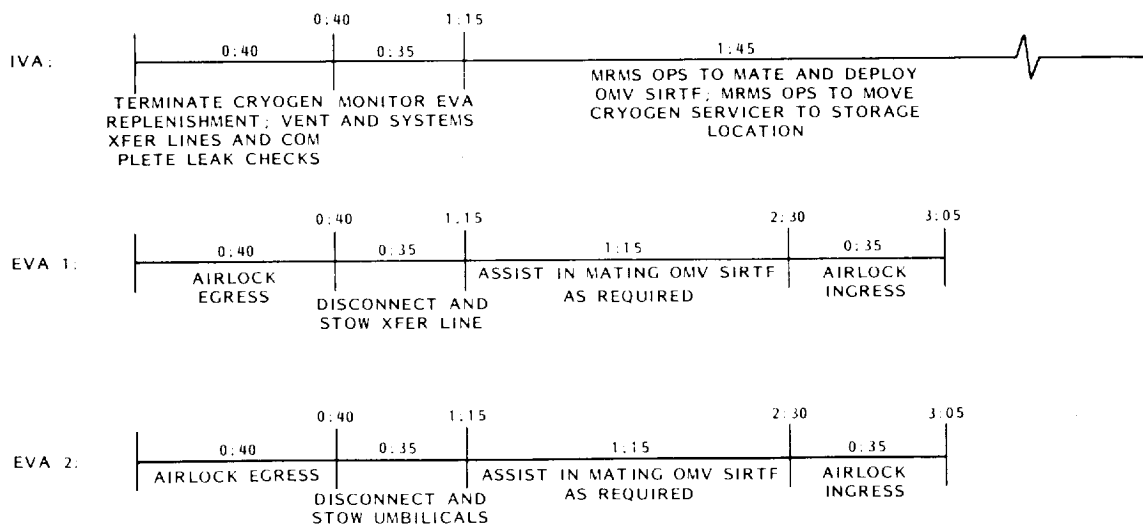


Fig. 5-20 IVA/EVA Timeline for Reference Mission 2

Figure 5-22 represents both the EVA and IVA tasks involved with the SIRTf servicer and OMV preparation in Reference Mission 3. This involves both the pre- and post-mission EVA/IVA activities. The servicer and the cryogen dewar are assembled on-orbit at the space station satellite servicing bay prior to the mission and are disassembled and stowed after the mission.

Figure 5-23 represents the activities and approximate times the remote servicer would require to complete the docking/checkout and ORU/replacement and cryogen replenishment on orbit. T_1 and T_2 vary depending on the mechanization of the service tasks.

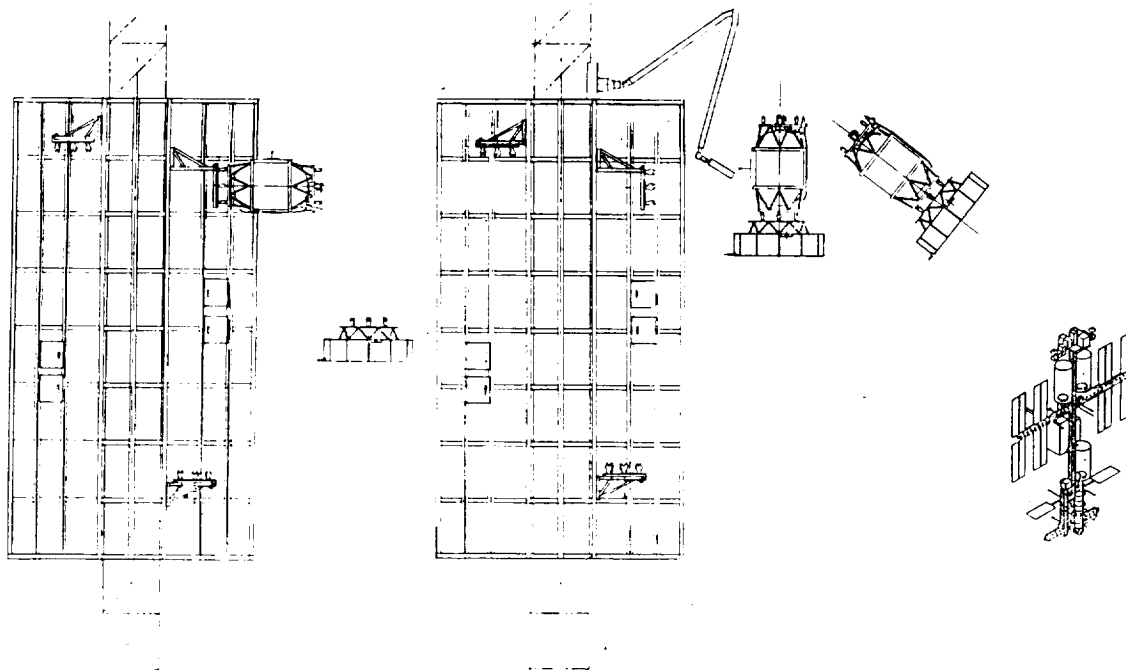


Fig. 5-21 Reference Mission 3 Concept

5.5 HUMAN FACTORS ASSOCIATED WITH SIRTf SERVICE MISSIONS

This section addresses man-machine interface in performing the reference missions. The equipment required for the astronaut is as follows:

- EVA Equipment:
 - 2 EVA suits and associated equipment
 - EVA cuff checklist
 - Portable and RMS foot restraints and work stations
 - EMU/payload bay lighting system
 - Wrist and waist tethers
 - Cryogen status and control unit
 - Cargo bay tool and ORU storage facilities
 - EVA tools
 - Tool caddy
 - Work station
 - Special cryogen handling equipment
 - Cryogen replenishment system controls
 - Cryogen transfer line and umbilicals
 - CCTV cameras
- IVA Equipment
 - Aft flight deck SIRTf and cryogen replenishment system software
 - Cryogen system status and control panel
 - CCTV equipment

OMV/SERVICER DEPLOY AND RETRIEVE OPERATIONS

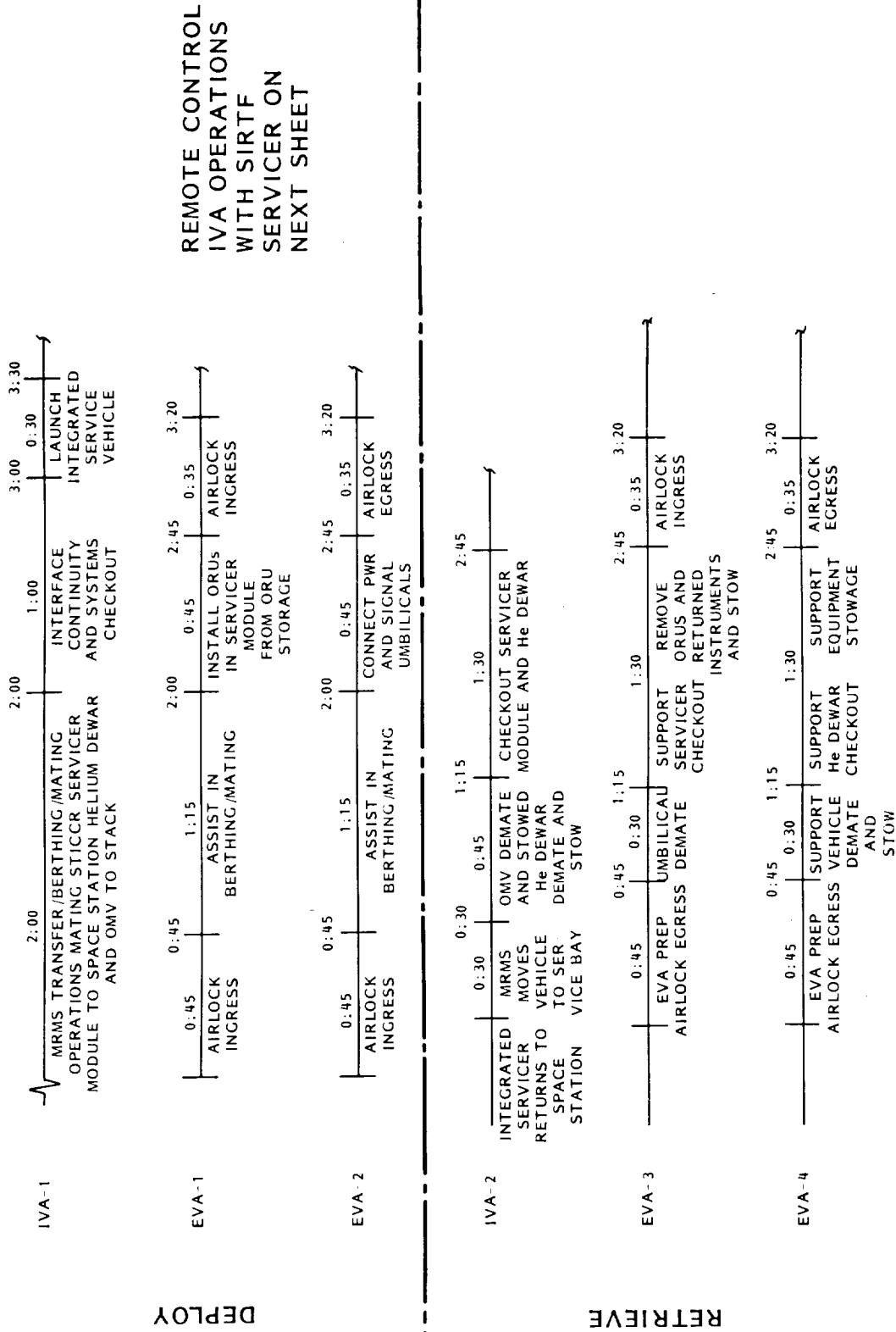


Fig. 5-22 IVA/EVA Timeline for Reference Mission 3

- OMV OPERATIONS TO DELIVER SERVICER TO WITHIN DOCKING RANGE OF SIRTf, APPROXIMATELY 16 HR, ARE NOT SHOWN

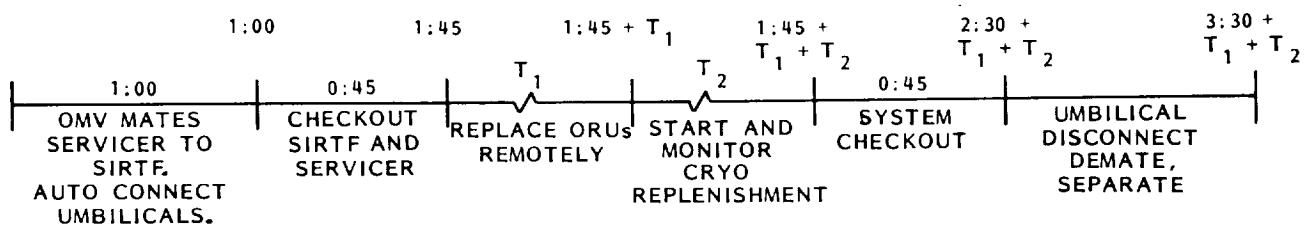


Fig. 5-23 IVA/Remote Control Timeline for Reference Mission 3

- EVA/IVA/ground communication and data system
- OMV special equipment not detailed

The manned SIRTf servicing issues include the following:

Work Envelope

- Berthing SIRTf and OMV at space station and orbiter
- Mate/demate of SIRTf/OMV
- Connection of electrical umbilicals
- Accessing ORUs
- Repair of non-ORU equipments
- Work around SIRTf solar arrays and antennas

Cryogen Equipment Handling

- Removing and restowing cryogen supply hose
- Avoiding contact with hazards
 - SIRTf vented cryogen
 - Supply tank vented cryogen
 - Hose vented cryogen
 - Burst disks fragments and released cryogen
- Performing contingency operations
 - Manual operation of failed valves
 - Manual supply line venting/purging

The work envelope concerns are common to satellites to be serviced/repaired. Because each satellite is configured differently, each provides a different set of operational constraints. The safety of each operation can be maximized by optimizing the design of the satellite for manned EVA servicing. The cryogen transfer equipment and operations development will include extensive detailed test and analysis to validate the concept for safe on-orbit operations and to deal with any contingencies.

Two observations relative to safety and cryogens in space are:

1. The space environment is much more convenient and safer than the comparable ground environment. The vacuum is free of condensable gases that are a prime cause of problems in ground-based cryogen handling.
2. A leaking cryogen in ground environment is readily visible. In space, a leak is likely to be invisible and presents a special hazard.

Figure 5-24 enumerates some of the safety considerations that must be taken into account for the STICCRS mission. Figure 5-25 shows the elements and interfaces associated with any manned space mission. The generalized concerns and design constraints associated with astronaut operations are continued in Figs. 5-26, 5-27, and 5-28.

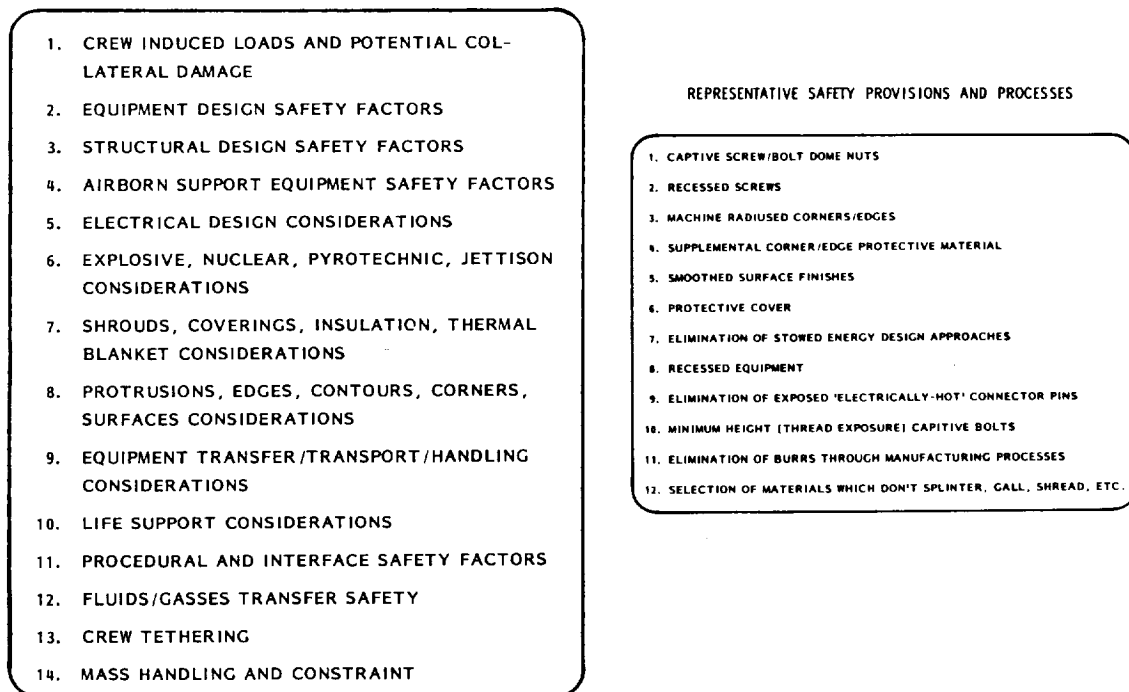


Fig. 5-24 Designing for Safety

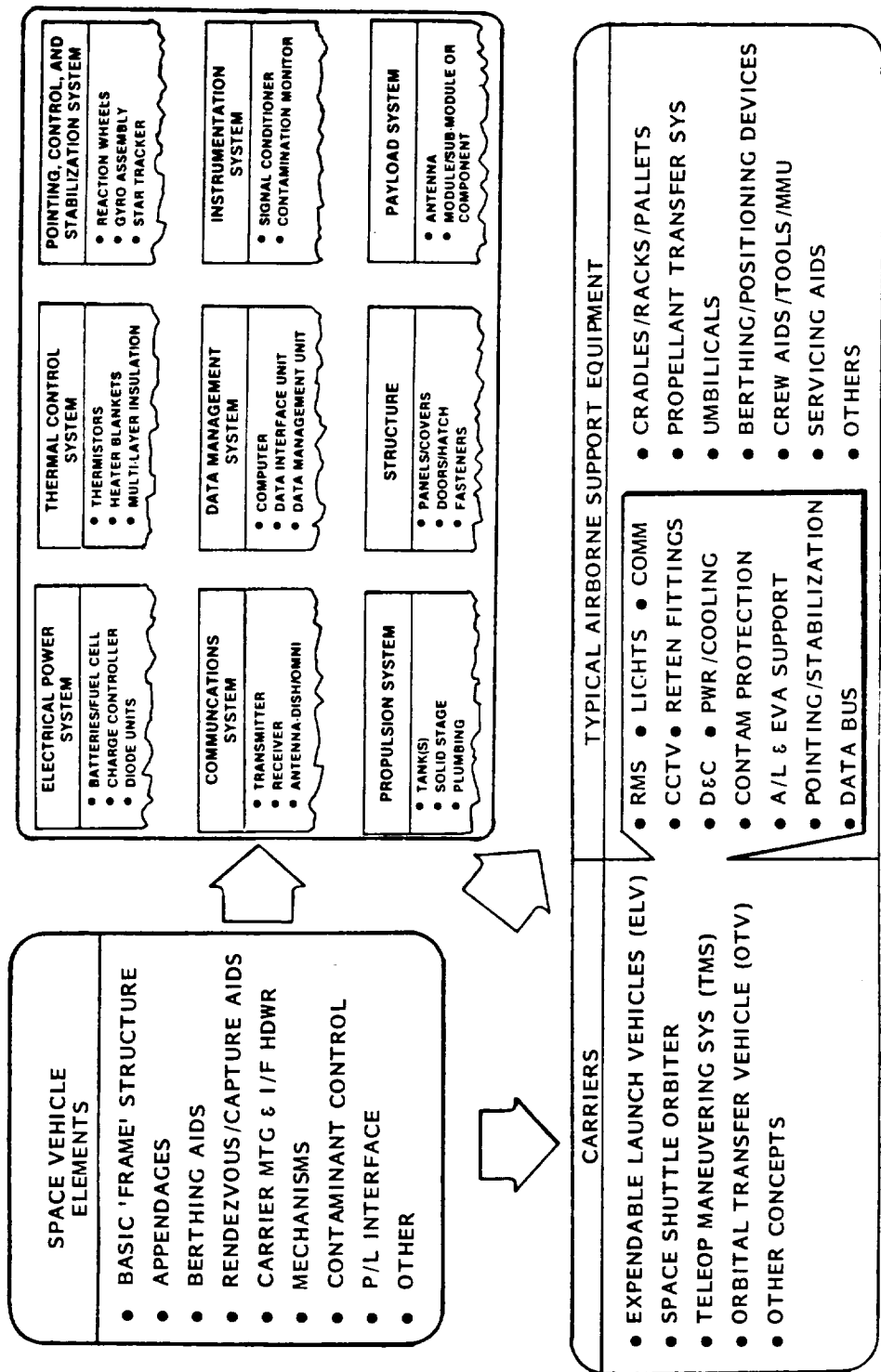
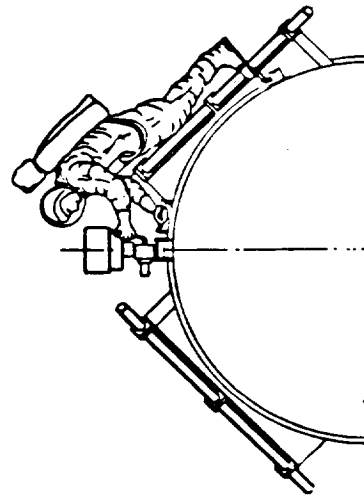
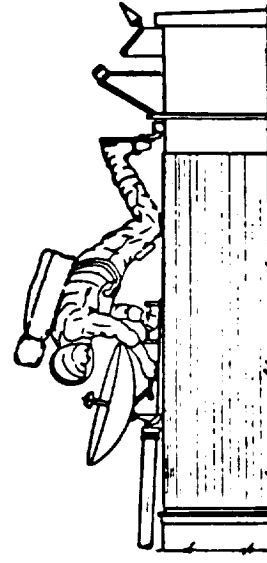


Fig. 5-25 Space Vehicle Elements and Interfaces

1. DESIGN FOR 5TH %TILE FEMALE TO 95TH %TILE MALE
2. SUITED CREW MOTION, REACH AND VISUAL ACCESS
3. TOOL SWEEP VOL UTILIZATION
4. CHANGEOUT ACCESS AND SWEEP VOL ENVELOPES
5. TOOL INSERT AND ENGAGEMENT ACCESS
6. VISUAL ACCESS WITH AND W/OUT HEAD/BODY MOVEMENT
7. ILLUMINATION PATH(S) TO WORK SITE
8. ASE INSTALLATION/INTEGRATION ACCESS
9. PROTECTIVE DEVICES (e.g., COVER) ACCESS AND STOWAGE
10. CONNECTOR/CABLE MANAGEMENT AND POSITIONING
11. MOTION OF APPENDAGES AND CREW LOCATIONS/ACCESS
12. LARGE ITEM XFER/XLATION/XPORT AND CREW ACCESS/SAFETY
13. ACCESS AROUND OR THROUGH STRUCTURE AND ADJACENT ITEMS
14. VISUAL ACCESS TO GUIDES, RAILS, ALIGNMENT AIDS, ETC.
15. ACCESS TO FASTENERS, HOLD-DOWN/RELEASE DEVICES, CLAMPS, ETC.
16. ACCESS TO UMBILICALS, e.g., OVERRIDES, DEMATE/REIMATE FEATURES



SOLAR ARRAY



HIGH GAIN ANTENNA

Fig. 5-26 Design for General Accessibility

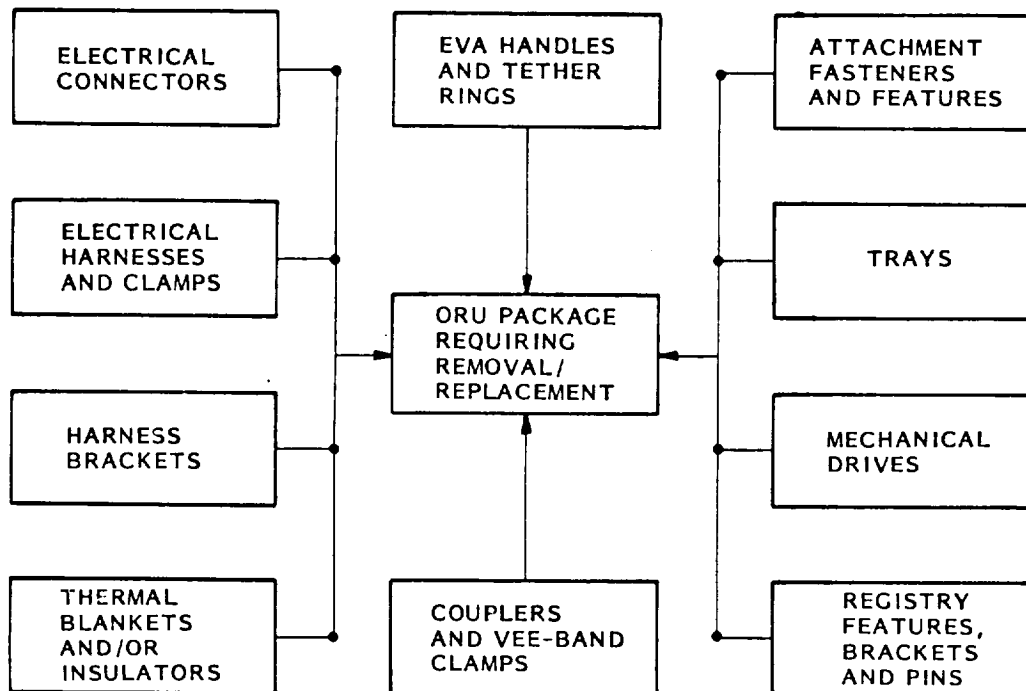


Fig. 5-27 On-Orbit Replacement Hardware Design for Changeout

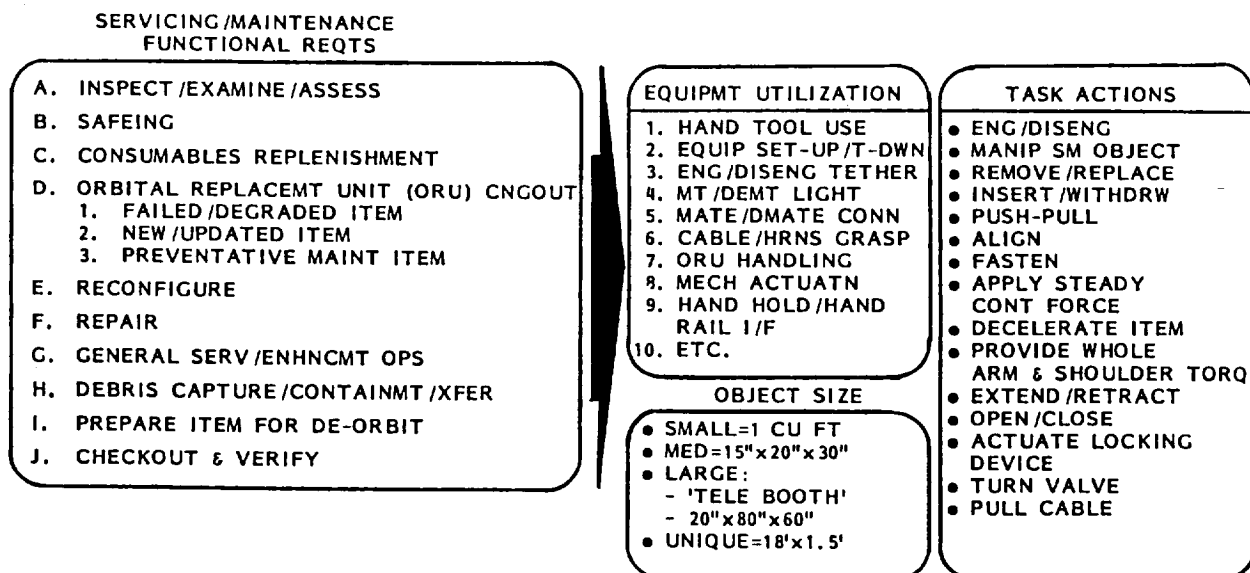


Fig. 5-28 Servicing/Maintenance Requirements and EVA Tasks

Section 6

STRAWMAN HELIUM TANKER AND SUPPORT EQUIPMENT

Table 6-1 presents the principal parameters of the He tanker. The system is designed for a He capacity of 10,000 L, which provides for both cool-down of a warm SIRTf system and refill of its presently baselined 4000-L tank. The storage lifetime of the system is 2 years with a 300-K outer shell temperature, and this is based on current storage technology similar to that purposed for SIRTf and other programs. This boil-off rate (0.14 percent/day) leads to substantial versatility in mission operations, since the tank could be stored in orbit or the space station for significant times without excessive losses. The predicted heat rate of 530 mW is based on use of the Passive Orbital Disconnect Supports (PODS) and three vapor-cooled shields. Further optimization will probably lead to increased lifetime, and substantial increases in storage life can be achieved by lower shell temperatures which can be achieved in orbit.

Table 6-1 SUMMARY OF STRAWMAN He TANKER PARAMETERS

LHe Capacity	10,000 L
Orbital Lifetime	2 years, 0.14 percent loss/day with 300-K outer shell temperature
Total Tanker Weight	3750 kg, includes 1250 kg He
Shape	Cylindrical with 2:1 elliptical ends
Length	349 cm
Diameter	250 cm
Thermal Protection System	3 vapor-cooled shields with 3-cm thick MLI blankets and PODS
Fluid Management System	Gallery surface-tension device
Transfer Technique	Mechanical pump or FEP
Low-G Venting Technique	Porous plug phase separator

The tanker employs a surface-tension device (gallery) to collect and supply LHe to the drain of the tank during transfer operations. Venting of the system is provided for in the low-g orbital environment by the porous plug phase separator. One plug is required for normal venting rates during orbital operation, while another substantially larger plug would be required for one version of operation employing the fountain effect pump (FEP). The necessity

of this large throughput porous plug vent has not yet been established, and development will be required if it is needed.

The transfer technique is assumed to be either a mechanical centrifugal pump or FEP. Selection of one over the other will affect the energy requirements and possibly the venting requirement. Details of the plumbing may be affected by the choice of pump. It is also assumed that a flow meter, possibly in the sump of the tank, will measure the LHe flow rate out of the tanker during transfer.

A cylindrical geometry with 2:1 elliptical ends was selected for the tanker shape. The overall shape and size of this tank is shown in Fig. 6-1, along with the dynamic envelope of the shuttle cargo bay.

The installation in Fig. 6-2 is designed for Reference Mission 1. Figure 6-3 uses a lightweight cradle to support the SIRTf replenishment dewar vertically within the orbiter cargo bay. For SIRTf positioning, the rotation table and berthing latches from the MSS flight support system (FSS) 'A' cradle are adapted for use in this system. It is supported by means of 12 truss members, off the forward dewar supporting ring.

Although a number of systems are available for supporting cargos in the STS orbiter, the dry weight of most of these devices is such as to limit severely the amount of lift capacity left for cargo. The cradle shown in Fig. 6-4 is

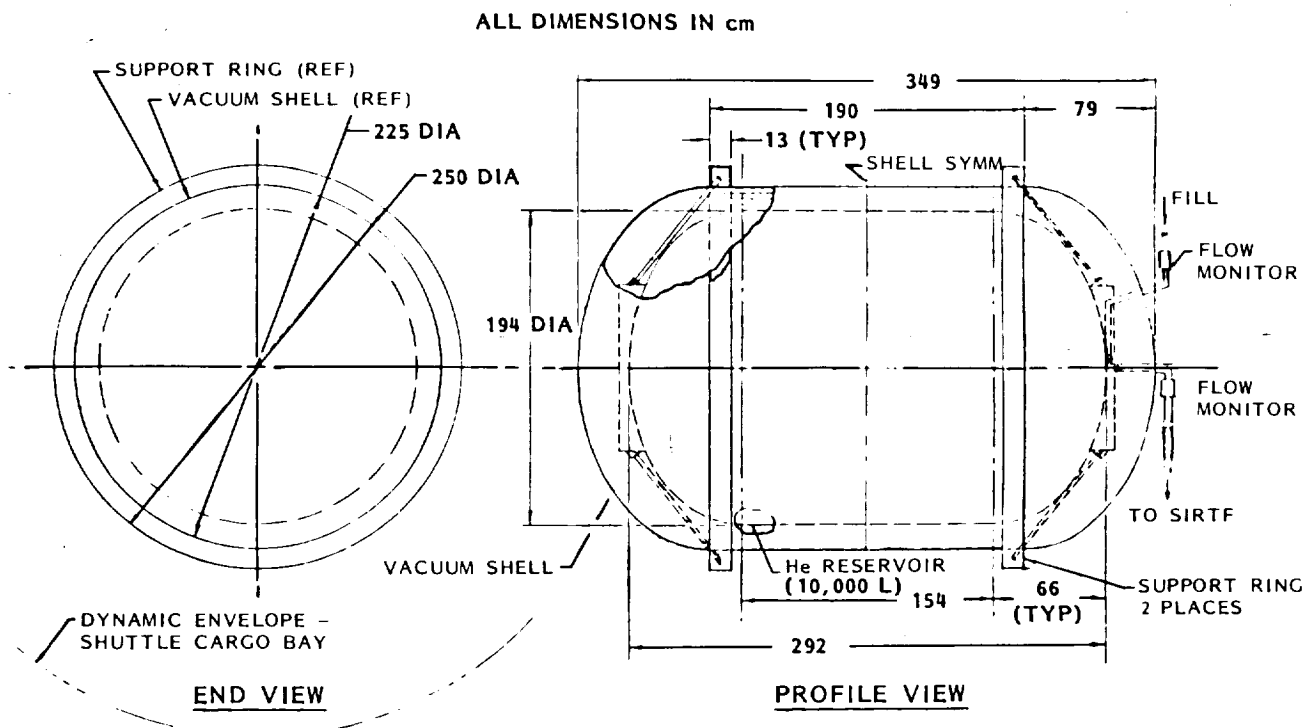


Fig. 6-1 SIRTf Cryogen Replenishment Dewar Tanker (10,000 L)

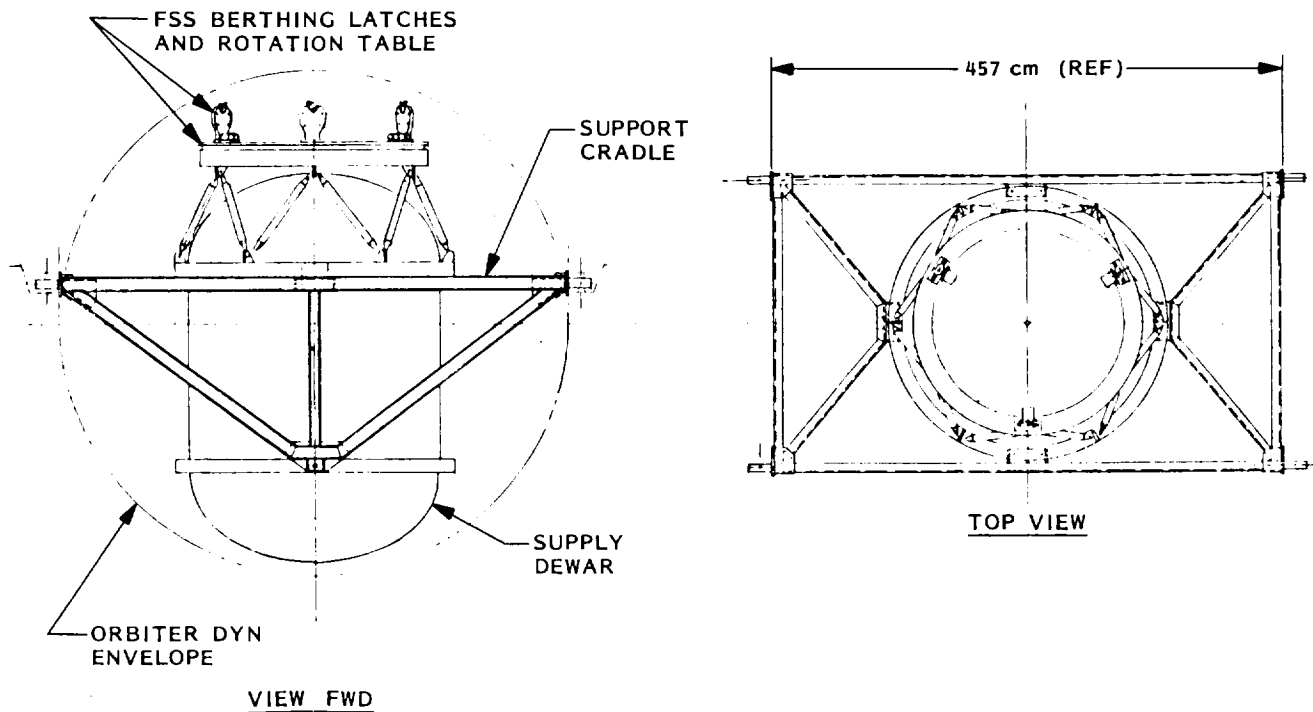


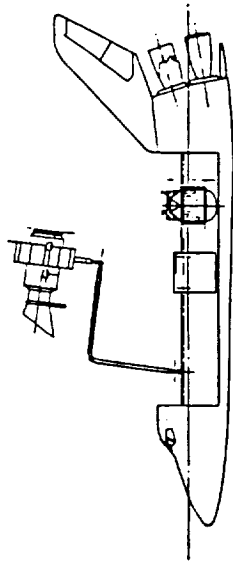
Fig. 6-2 Vertical Installation of Replenishment Dewar in Orbiter

designed specially for logistic support of the baseline replenishment dewar for SIRTf and achieves a relatively low weight (500 lb) through use of the dewar support rings as an integral part of the cradle structure. It is also designed to remain in the orbiter when the dewar is transferred to space station. This eliminates the need for heavy, automatic sill retention/release fittings.

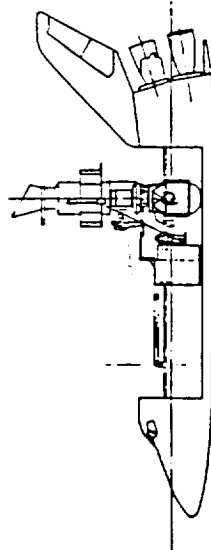
In previous studies entailing provision of servicing facilities for space station, one of the more attractive candidates was the double bay arrangement shown in Fig. 6-5. In addition to the large increase in servicing capabilities within the given space, this facility also permits use of up to four rail-mounted logistic trolleys for berthing, handling, and transfer of spacecraft, OMVs, servicing equipment, etc. These devices incorporate the key handling elements of the FSS system, and, together with the double bay facility, serve as a basis for the STICCR Reference Mission 2 scenarios. To perform the SIRTf cryogen replenishment from the space shuttle with or without the aid of the OMV, the orbiter must carry the cryogen replenishment tank along with its ASE (and the OMV). These are conventional payloads. No extraordinary requirements are placed on the STS hardware.

The long time required to replenish a warm SIRTf extends the shuttle flight duration to near its limits. This is expensive both in the time the shuttle is out of service to other users and in the reduction in payload that can be carried on the long missions.

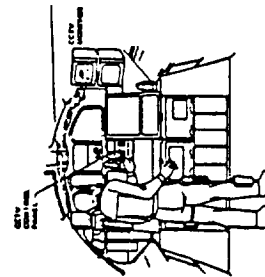
1. SHUTTLE CAPTURES SIRTf



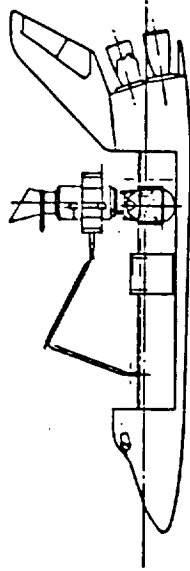
3. EVA FOR INSTRUMENT/ORU CHANGEOUT



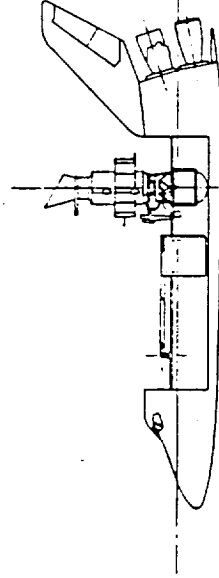
5. IVA MONITORING CRYO REPLENISHMENT



2. RMS BERTHS SIRTf ON CRYOGEN REPLENISHMENT SYSTEM



4, 6. EVA TO CONNECT AND DISCONNECT CRYO TRANSFER LINE



6. RMS USED TO DEPLOY SIRTf

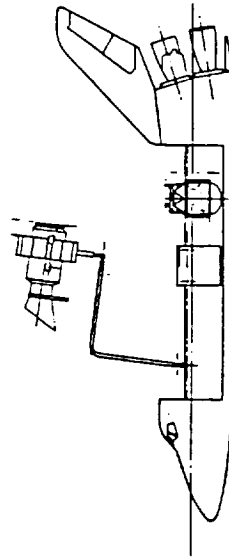


Fig. 6-3 Reference Mission 1 Concept

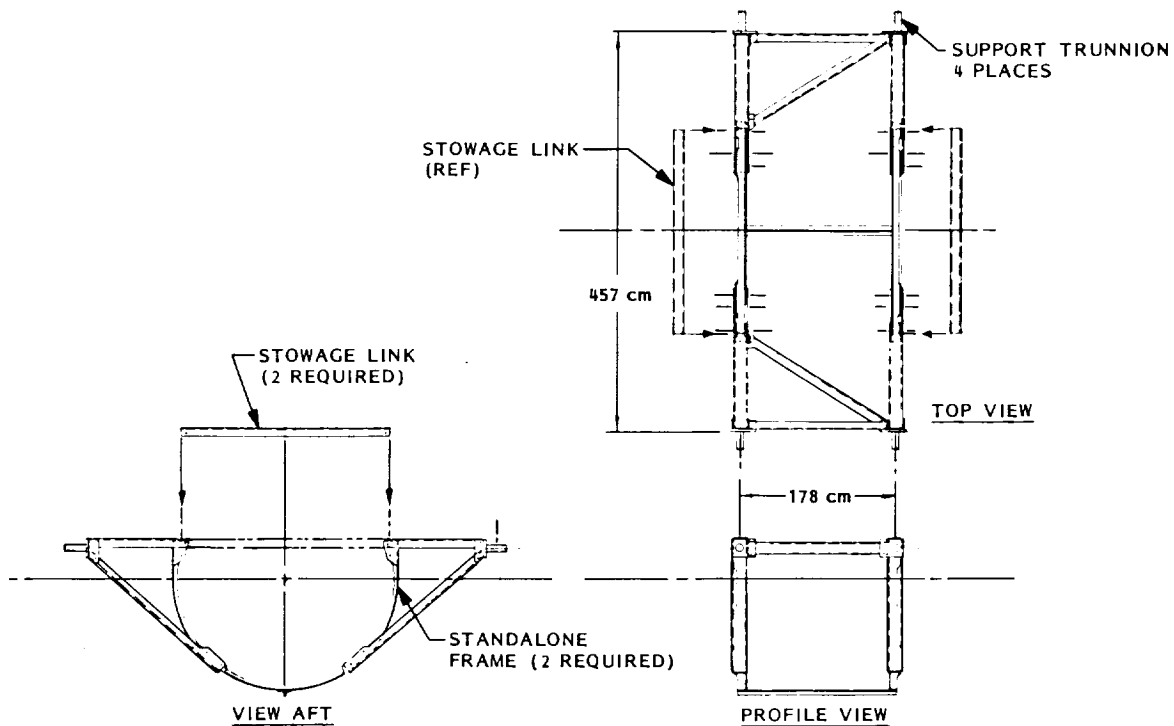


Fig. 6-4 Cradle for Transport of Space Station Replenishment Dewar

The mission duration could be significantly shortened if the replenishment could be planned with assurance that the SIRTf had not warmed. Even so, the desire for instrument changeout may require a warm SIRTf and further lengthens the mission. The impacts of SIRTf cryogen resupply on the space shuttle are:

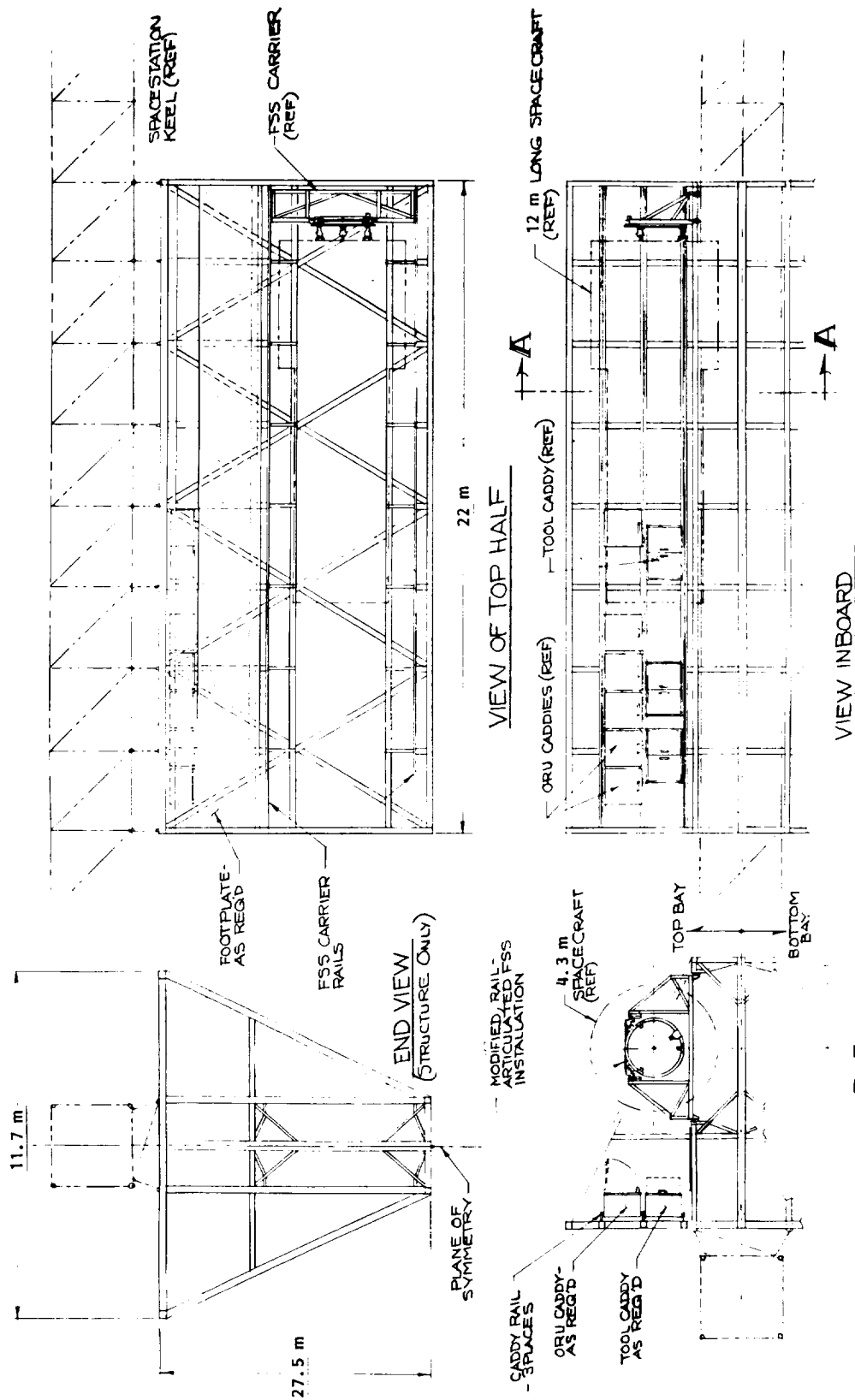
Hardware

- Payload accommodation for helium supply dewar—conventional man-rated ASE for He transfer, e.g.,
 - Protection from sharp corners
 - Handholds, foot restraints, tether attach points within work envelope
- Instrumentation for IVA monitoring and control of process

Operations

- Likely mission duration - 12 to 14 days
- Dual launch of space shuttle required to separately deliver OMV and He tank to orbit from which resupply of SIRTf in preferred sun-synchronous orbit can be achieved

The hardware impacts on the space station are accommodation of the cryogen replenishment system (CRS) and SIRTf. The baseline concept calls for the replenishment ASE [without cryogen replenishment dewar (CRD)] to be carried to the station on a routine resupply and stored there for the duration of the SIRTf mission. The CRD would then be delivered shortly before the



W/CRAVE
11/8/84
1" = 10 FT
1" = 120 IN

Fig. 6-5 Double Bay Servicing Facility

replenishment operation and subsequently returned to earth for storage, maintenance, and refill prior to the next service mission. Thus, the long-term physical impact on the space station is the occupation of space for the CRS.

Other effects appear to be as minimal as space utilization:

- The SIRTf and its ASE cannot contaminate the station or other users
- It has no impact on the station life
- The CRS will require periodic maintenance at the replenishment cycle
- The power and thermal loads are expected to be small compared to other space station users

More detailed considerations are:

- ASE stored on space station
 - Cryogen replenishment system
 - Instrumentation and control subsystem
 - Specialized EVA tools
- Likely effects on space station
 - Contamination - none
 - Potential contamination of SIRTf by effluent of life support system or propellant resupply system
 - Lifetime - none
 - Service and maintenance
 - Use of OMV will increase required service and maintenance of OMV
 - Permanent housing of instrumentation and control ASE would require maintenance and service at the replenishment period (1 to 2 years)
 - Thermal and power
 - Replenishment system expected to utilize minimal power at widely separated intervals 10 to 12 days on 1 to 2-year cycle
 - No specialized thermal loads or constraints are inherent in storage of the equipment or the He dewar
 - Structures
 - SIRTf replenishment will use normal standard structures and mechanisms incorporated in the space station service bay. For example, berthing mechanisms similar to the MMS FSS will be required, and two mobile remote manipulators (MRMs) will be required to handle SIRTf and OMV simultaneously.

To be replenished using astronaut connect/disconnect, SIRTf and its ASE must be man-rated. This will employ the conventional approaches to man rate other satellites as follows:

- Provision of electrical and mechanical interfaces to mate with
 - OMV
 - RMS
 - Space station service bay
 - Shuttle orbiter bay
 - Replenishment ASE

- Instrumentation and control for remote control of He transfer process
- Human engineered access to fill port
- Retractable/furlable solar arrays and antennas
- Least reliable equipment made multiply redundant and/or designed as orbit replaceable/repairable units (ORUs)

The interface requirements designed into the SIRTf will include all elements used in the final replenishment plan.

Flow meters and other instrumentation must be incorporated specifically for the on-orbit transfer of cryogen. It is expected that most instrumentation and control elements will serve the dual purpose of space and ground loading and handling.

The transport and docking of the operational SIRTf implies that the appendages be so designed to either take the acceleration loads and not interfere with access to the dewar, telescope, and spacecraft equipment bays, or be removable, furlable, or otherwise managed to provide the necessary accesses. The reliability discussion indicates that SIRTf must be provided with a high level of redundancy to attain as high MTTF as is feasible.

SIRTf replenishment from the orbiter (Reference Mission 1) requires a dedicated payload panel to monitor and conduct the cryogen operations and to monitor and control SIRTf while it is mated to the cryogen replenishment system (CRS), Fig. 6-6. The information that the panel processes includes: temperatures of the SIRTf cryogen tank, telescope instruments and vapor-cooled shield; temperatures of the dewar, transfer line, vapor-cooled shield porous plugs and thermo pump; operation and status of the SIRTf cryogen transfer valves; operation and status of the supply dewar, and the dewar transfer lines, liquid/vapor flow control valves and pump; pressures in the SIRTf tank, and vent lines; pressures in the dewar and transfer line; flow meter information on the dewar vapor and liquid flow, SIRTf transfer vent flow, and normal orbital/vent flow. This considerable amount of information is made available to the mission specialist. A separate panel may be provided to check out the health and status of SIRTf and spacecraft subsystems.

Table 6-2 presents a preliminary power estimate for accomplishing the cryogen resupply from the orbiter. The Lockheed command and monitor panel (CMP), developed in conjunction with the experiment support system, requires 175 W for its microprocessor and CRT power supplies. This unit will perform the required computations and limit checks, and will permit keyboard entry of data and instructions. The unit, mounted at the aft flight deck payload station, is powered from either fuel cell 1 or 2.

A command and telemetry unit (CTU) is required to interface between the CMP and the payload (in this case the CRS) in order to convert the CMP logic signals to relay driver outputs required to operate payload devices. The CTU, powered from fuel cell 3 (normal power source for payloads in bay), draws 55 to 60 W.

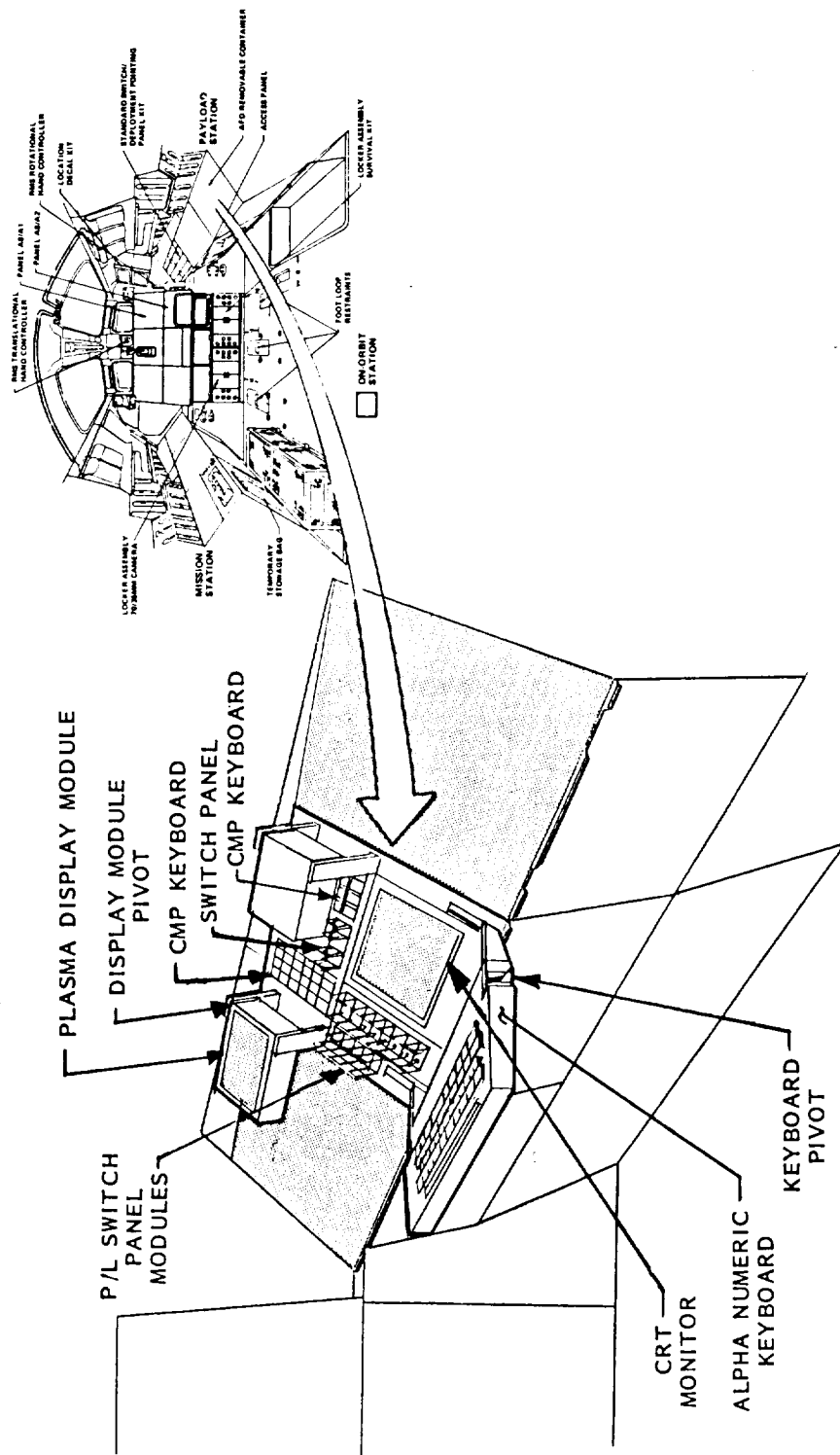


Fig. 6-6 Orbiter Workstation Aft Flight Deck Payload Console Concept

Table 6-2 PRELIMINARY POWER REQUIREMENTS FOR LHe TRANSFER
FOR SIRTf REFILL

During transfer:		
1. LHe transfer pump		10 W
2. Flow control valves (10 each) 10 duty cycle, 12 W/valve		12 W (avg)
3. Flow meters (2 each) - estimated at 10-W each		20 W
4. Command and monitor panel with microprocessor and CRT power supplies		<u>235 W</u>
Total (estimated)		277 W
Contingency mechanical refrigerator for extended storage of LHe in supply dewar: cooling load 15 W at 60 K		
		500 W
Standby: Monitoring instrumentation		2 W

We also considered providing a mechanical refrigerator to cool a shield in the thermal system of the He tanker. Assuming a 15-W cooling load at 60 K, approximately 500 W of power would be required for a stirling cycle unit. This cooling could substantially increase the storage time of the dewar and may be desirable for some scenarios involving space station operations.

Foot restraints are necessary during the SIRTf EVA activities. The foot restraint shown in Fig. 6-7 enables the EVA crew member to apply force to change out ORUs or to translate any piece of equipment. The foot restraint has 3 deg of rotational freedom. This affords the EVA crew member maximum flexibility in gaining access or exerting forces.

Table 6-3 summarizes the weights of the major elements of the He tanker along with its support equipment, and Table 6-4 shows more details of the cradle for the dewar.

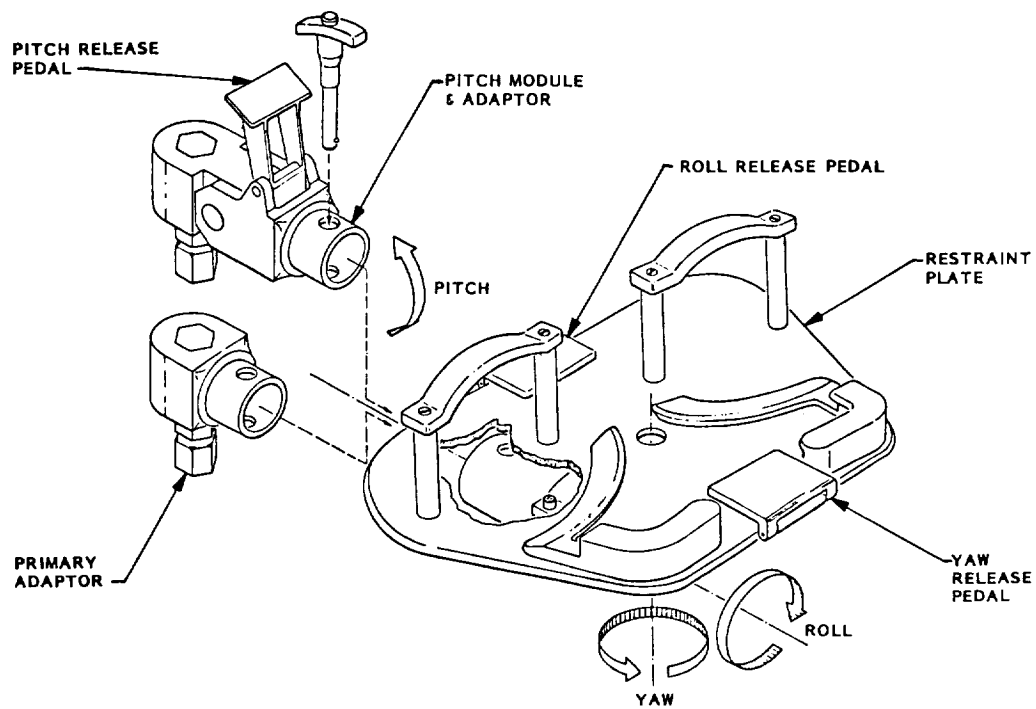


Fig. 6-7 Foot Restraint Assembly

Table 6-3 AIRBORNE SUPPORT EQUIPMENT WEIGHT SUMMARY

	<u>kg</u>
Dewar	2500 dry
LHe	1250
Cradle	455
Control Box (Cradle)	20
Control/Monitor Power (AFD)	35
Cabling/Harness/Wire Trays	100
Xfer Lines/Valves/Gages	50
Crew Charges (4M/8D)	<u>39</u>
Total ASE Weight	4449 (9788 lb)

Table 6-4 DEWAR CRADLE SYSTEM WEIGHT SUMMARY

Item	Weight	
	lb	kg
Fore and aft transverse trusses (2) (includes attach fittings)	230.6	104.6
Fore and aft links (2)	48.3	21.9
Draw braces and att. fittings	31.5	14.3
Berthing platform supports (12)	11.3	5.1
Berthing platform (lightweight)	44.0	20.0
*Berthing platform rotation drive (FSS)	30.0	13.6
*Berthing latches (FSS) -- (3)	109.2	49.5
*Electrical umbilical (FSS)	22.8	10.3
Support trunnions (in orbiter) -- (4)	<u>120.0</u>	<u>54.4</u>
Subtotal	862.7	391.3
Growth Contingency (20 percent of new items)	<u>140.1</u>	<u>63.6</u>
Total weight:	1002.8	454.9

*Items which are flight qualified

Section 7

TECHNOLOGY PLAN

Much new technology remains to be demonstrated and proven prior to operational replenishment of superfluid helium systems in orbit. Although there are a substantial number of components which must be proven, and several serious issues concerning the transfer thermodynamics of the system to be established, most of the development can be demonstrated on ground tests. The crucial question regarding the cost and schedule of this development is the degree to which systems operation must be proven in orbital test.

The technology plan focuses on two areas: (1) the required development of components required for orbital He-II transfer, (2) system-level testing in which transfer from tank to tank is demonstrated. This plan presents assessment of the state of technology of various components or elements along with the required development, cost, and schedule. Although the following components will require development, the relative importance and need for these elements may vary depending upon a detailed thermal systems analysis which may lead to a specific system selection.

Additional development is required on the following components:

Pumps

- Mechanical pumps
- Fountain effect pump

Low-g liquid drain system for He-II

Low-g venting system for LH₂ (if SH₂ is used on SIRTf)

Low-g phase separators for He-II (high vent rates)

Instrumentation

- Mass gaging in low-g
- Flow meters
- Cold pressure transducers

Cold shut-off valves

- On-off type
- Modulating type

Low heat leak transfer lines and fittings

High thermal conductance thermal links

- Shrink-fit type
- Others

Although the status and requirements of many of these systems have been described in this report, a brief synopsis of the technology requirements and plan for these elements follows.

Item: Mechanical pump used to transfer LHe-II

State of the Art: The only test data for transfer of He-II was that of a centrifugal pump driven by a submersible, three-phase induction motor, tested in a 1.9-K He-II bath at the National Bureau of Standards (NBS), Boulder, Colorado (Ref. 7). Test data include static pressure rise, motor power consumption, and liquid He-II volume flow rates measured by a Venturi meter. Pump tests (Ref. 22) were done in normal LHe only. Presently, NBS is again developing and testing a centrifugal pump to transfer LHe-II under a contract from NASA/Ames Research Center. The performance of such a pump is the title of a paper to be presented by Gene Steward at the Helium Transfer in Space Workshop, 20-21 August 1985 at NBS.

Required performance or improvement for SIRTf instrument changeout and cryogen replenishment (STICCRS): The efficiency of the NBS pump in He-II flow should be determined by more accurate data of the fluid flow rate and the flow work. A centrifugal pump similar to the NBS design should be tested in the He-II steady flow conditions, i.e., transfer of He-II from a supply tank to a receiver tank. In addition to the motor power input, the recorded data should include the temperature and pressure change between the pump inlet and outlet, as well as that in the supply and receiver tanks. The He-II flow rates can be determined by liquid-level indicators and/or radiation mass gages. Literature search should be continued on displacement devices like piston, membrane, and bellows pumps for comparison of various types of mechanical pumps on the basis of total efficiency.

Cost/Schedule: The present development of the pump at NBS should be continued at the component level. At the completion of that phase the pump should be implemented into a ground test facility including supply and receiver tank. The cost and schedule are included in the overall plan for the ground testing.

Item: Fountain effect pumps (FEP) used to transfer LHe-II

State of the Art: Available in open literature are (a) critical velocity of flowing LHe-II in narrow channels and porous plugs, and (b) fountain pressure data. Test on a fountain effect pump (or thermomechanical pump) in a ground based experiment and design of an attached shuttle demonstration experiment to fly on the Hitchhiker/Shuttle Payload of Opportunity Carrier mode are being conducted at Goddard Space Flight Center (GSFC). The concept has been described by M. J. DiPirro at the AIAA 20th Thermophysics Conference, 19-21 June 1984 ("On-Orbit Transfer of Superfluid Helium Using the Thermomechanical Effect," M. J. DiPirro et al.) and in another paper, "Superfluid Helium Transfer in Space using the Thermomechanical Effort," M. J. DiPirro, to be presented at Helium Transfer in Space Workshop, 20-21 August 1985 at NBS. One of the objectives of the GSFC experiment is to measure the pressure drop along a fully turbulent line of He-II.

Required Performance or Improvement for STICCRS: Data are needed on (a) heat transfer rate from the porous plug to LHe-II, (b) steady flow data of FEP operation, and (c) heater details, particularly the vortex shedding-caused departure from the ideal superleak situation where liquid is transferred as superfluid at zero entropy. Ground tests can be conducted to obtain these data by using the same tanks as for test on the mechanical pumps and using a FEP in place of the mechanical pump.

Cost and Schedule: Individual FEP assemblies should be constructed and tested in a relatively small simple apparatus to determine performance. The estimated schedule is 5 man years over 2 years. The FEP assemblies (including heater) should then be implemented into a ground test facility.

Item: Low-g vapor-liquid phase separator (VLPS) for high vent rate of He-II dewar

State of the Art: The VLPS porous plug mounted on the IRAS dewar was reported to have a vent rate of 2.36 mg/s at 1.72 K, decreasing to 1.68 mg/s at 1.6 K. A comprehensive review and comparison of the results of different research groups engaged in He-II VLPS is given in Ref. 37. The highest flow rate reported is below 9 mg/s at pressure gradient of 2.9×10^5 Pa/m in a ceramic alumina porous plug (Murakami, et al., ISAS Report, Jan 1984).

Required Performance: Ground test can be conducted on a parallel packed-power unit as shown in Fig. 3-32 and extended surface like the Surfamax shown in Fig. 3-33 to obtain the optimum configuration for vent rates close to 4 g/s.

Cost/Schedule: Individual phase separators should be tested in laboratory apparatus similar to prior porous plugs. The high vent rates may be difficult to achieve with ordinary pumping systems. The schedule estimate is 5 man-years over 2 years. The cost of the pumping system is TBD.

Item: Gallery surface tension device for draining LHe-II.

State of the Art: The technology for using surface tension devices to drain cryogenics under low-g are now being developed. They have been used extensively on storable propellants. The gallery device is under development for LH₂ with the NASA Cryogenic Fluid Management Facility (CFMF) to be conducted in approximately 1989. NASA-Goddard is developing an on-orbit He-II transfer system that uses a sponge-type design. It is a partial control device usually used for a buffer during short-duration flow and acceleration transients. Its use in a 10,000-L tank with He-II may not be adequate to allow for low residuals under all expected accelerations. Since the gallery device is a total communication device under fairly high accelerations, it appears to be the best choice for the transfer of He-II.

Required Development: It is expected that by use of nondimensional scaling factors, the CFMF results can be used for demonstration of acquisition of LHe with the gallery-type device. Development tests are also required.

Ground Tests: Experiments are required to evaluate the effectiveness of screens to provide capillary pressure differences with LHe. Generally tests of screens have been made with storable fluids and then scaled, using a standard approach, for cryogenic fluids. Numerous experiments have been conducted for O₂ and H₂ where measured values have correlated well with predicted methods. Due to the large difference in surface tension of LHe compared to these other fluids, these tests should be conducted with LHe.

A second test should be conducted to determine the actual flow characteristics of the liquid through woven screens. Analytical models have been adapted to predict characteristics of fluid flow. It would be important to determine if these analyses can be applied to He-II. Drop tower tests can be performed to determine the actual fill times of the galleries once the device is injected into a low-g environment. Typically these tests have been performed for this type of device with properly scaled models.

Orbital Tests: Tests of the ability of gallery type devices to achieve low residuals at depletion have generally been ground tests. Due to the very low surface tension, these tests with properly scaled models may be difficult in a one-g environment and could lead to requirement for an orbital test. If the ground tests of He-II characteristics agree with predictions, perhaps the device need not be demonstrated in orbit.

Costs:

Orbital Tests: TBD

Ground Tests: 4 man-years over 2 years

Item: Metal Foam for fill and retention of LH₂ during high venting rates and low-g.

State of the Art: Metal foams have been used for low-g heat exchangers with solid cryogenics. In the SIRTf H₂ tanks, metal foam is also of particular interest since it can maintain liquid under fairly high g levels while the tank is being vented during solidification. The main concern is its ability to be filled and achieve high fill levels without trapping large amounts of vapor.

Required Development: Analysis and tests are essential to verify the filling, venting, and solidification of H₂ in a metallic foam.

The driving parameter in determining the success of filling the foam is the liquid velocity profile. Generally the acceleration direction and flow rate are the dominant factors in filling tanks. In this case, the characteristics of the foam would dominate. Therefore, it appears possible that a series of successful tests in one-g will provide enough confidence that a low-g application will also be successful.

Ground Tests: 1 man-year over 1 year

Orbital Tests: None required

Item: Cold shut-off valves

Shut off valves will be used extensively for the cryogen replenishment. These valves will run at 1.5 to 4 K and be He-II tight. They must be remotely commandable and extremely reliable. No requirement for a modulating valve has been found, but this is a possible requirement.

State of the Art: The only flight-qualified He-II valves developed are those used on IRAS and COBE. The IRAS valve had operating problems, the COBE valve has evidently successfully been qualified, and valves for the GP-B program are under development. The COBE valve may be adequate for the requirements here, but different size valves or modulating valves may be required. The requirements need further definition.

Required performance for STICCRS: Performance parameters are TBD.

Cost/Schedule: The estimated cost of such a development is 0.5 M to 2 M over several years. The favored approach is to work with a valve manufacturer on development.

Item: Low heat leak transfer lines and fittings

The importance of the heat transfer losses of the transfer line and associated connecting fittings (bayonets) is not clear at this time. For the nonvented transfer using a mechanical pump, the losses due to the transfer line were fairly small. For the transfer using the FEP, it appears that some heat addition to the fluid in the receiver tank may be necessary due to the mechano-caloric effect in the porous plug. This heat addition could be satisfied by heat leaks in the transfer line. In spite of these possible advantages of heat addition in the line, it is expected that in the final analysis it will be desirable to minimize this load.

State of the Art: The heat load assumptions for current transfer lines and bayonets are described in Section 3.5. These values are for commercially available lines which are not optimized with respect to minimizing heat loads. It is expected that fairly straightforward design improvements will substantially reduce heat loads. These can be obtained by improved MLI-type insulation and greater thickness on the line, and by longer sections on the bayonet connections. Improved bayonets are in design.

Required performance For STICCRS: The final values are TBD, but substantial reductions in head load may be attainable and desirable.

Cost/Schedule: The program for this technology development would be approximately 2 man-years for 2 years.

Item: High thermal conductance thermal links

Efficient cool-down of a warm SIRTf tank requires excellent thermal grounding between the cold telescope components and the He tank. If the tank and telescope closely approach an isothermal mass during cool-down, the most economical (least volume) replenishment occurs. This can be achieved by good thermal shorting between tank and telescope and/or by proper routing of the vent gas. The thermal link requirements are addressed here.

State of the Art: Most cryogenic systems have employed flexible copper braids for areas that require flexibility or are not detachable, or bolted joints for removable components. The bolted joints in general lead to nonrepeatable and unpredictable thermal contact. We have had extensive experience with epoxy-bonded joints, which employ thin bond lines and large areas, and shrink-fit joints which rely on dissimilar materials for high pressure in the joint. These techniques have been used on flight hardware at temperatures of 15 to 70 K. In addition, instrument changeout approaches employ shrink-fit assemblies, particularly where access to bolted joints is not possible.

Required performance for STICCRS: Approximate calculations indicate that epoxy bonding or shrink-fit joints can provide the required joint conductance at the SIRTf temperatures (1.5 K), but the analysis is complicated because of the Kapitza resistance and unknown details of surface conditions. Experimental measurements are required down to 1.5 K on candidate joint types.

Cost/Schedule: The development would require 1 to 2 man-years for 1 year.

Item: Instrumentation

To monitor the filling operation progress and efficiency it is desirable to measure flow rate of liquid and vapor in supply and receiver tanks and to determine the total mass in the tanks at any given time. It is also desirable to accurately know the SIRTf He mass remaining during orbital operation so that the replenishment mission can be properly planned to avoid tank warm-up. The helium mass inventory at any time is a crucial quantity during operations. It is also necessary to monitor pressure in various parts of the system during resupply. Some of the instrumentation to accomplish this are flow meters, for vented gas and liquid transfer rates, mass quantity gages in tanks, and cold pressure transducers.

State of the Art: There are no development programs in progress at this time known to the authors, although it is believed that a zero-g, cryogenic mass gaging contract may be let in the near future. IRAS uses liquid-level sensors to determine tank fill on the ground to establish initial loaded mass. Expenditure in orbit was determined by an orifice type gas flow meter in the vent line. It is believed that approximately 20 percent accuracy was achieved with these techniques. A suggestion by Castles et al., NASA-Goddard, for a mass gaging system which uses a small heat input and the resulting He temperature rise ($\Delta T \sim 0.001$ K) to determine He mass would appear to warrant

further study. This approach is unique to He-II because of the uniform temperature due to the extremely high heat transport.

Required Performance for SIRTF: Many of the current techniques will give a reasonably accurate measurement of mass quantity in the tanks under the relatively quiescent conditions of orbital operation where atmospheric drag will locate the fluid in a predictable manner in the tanks. Under the dynamics of fluid transfer, the disturbing forces associated with fluid flow might overcome the small static forces orienting the fluid and make the task of predicting the fluid attitude impossible. Most mass gaging techniques require knowledge of fluid attitude, so mass determination becomes accordingly difficult. Techniques need to be devised to measure the mass in the SIRTF tank.

In addition we have suggested that a sudden increase in the receiver tank pressure due to hydrostatic pressure would occur in a nonvented system at the time of 100 percent fill. This would occur for both the mechanical and fountain effect pumps and would greatly simplify the knowledge of a filled tank condition. For a nonvented receiver tank, the mass inventory is greatly simplified because only a measure of the flow rate of liquid into the tank is required, and there is no vented gas or liquid to monitor.

Development Plan: The requirements need to be established for both monitoring cryogen mass under operational conditions and under conditions of transfer. The techniques used may differ if the transfer occurs from the shuttle or from space station. Techniques to meet these requirements need to be traded and the most promising tested for their applicability in He-II. Orbital tests follow on the system(s) of choice.

Costs/Schedule: 1-5 M, 2 years plus orbital tests

As indicated in the data sheets, most of the components can be demonstrated in relatively inexpensive ground test and do not depend upon the orbital acceleration. A notable exception is the low-g fluid management system for draining liquid. The performance of several of the elements cannot be fully characterized without setting up a tank to tank transfer experiment with carefully controlled variables. Both candidate pumps fall into this category, and the importance of reducing the heat load from the transfer line and couplings is not completely clear since some analyses indicate the need for heat input to the receiver tank fluid to establish thermal equilibrium in the system.

Figure 7-1 presents an overall flow plan of the technology development. Additional systems analyses are required for the system. Although the system analysis for the top-off or refill of a cold tank is relatively straightforward as far as analysis can go without additional test data on systems and components, analysis of the cool-down and refill of a warm tank is complex and requires coupling of the heat transfer, thermodynamics, and fluid flow to perform the analysis. There are also more options for efficient filling of a warm tank. For these reasons we feel that additional system analysis should be performed early in the technology development.

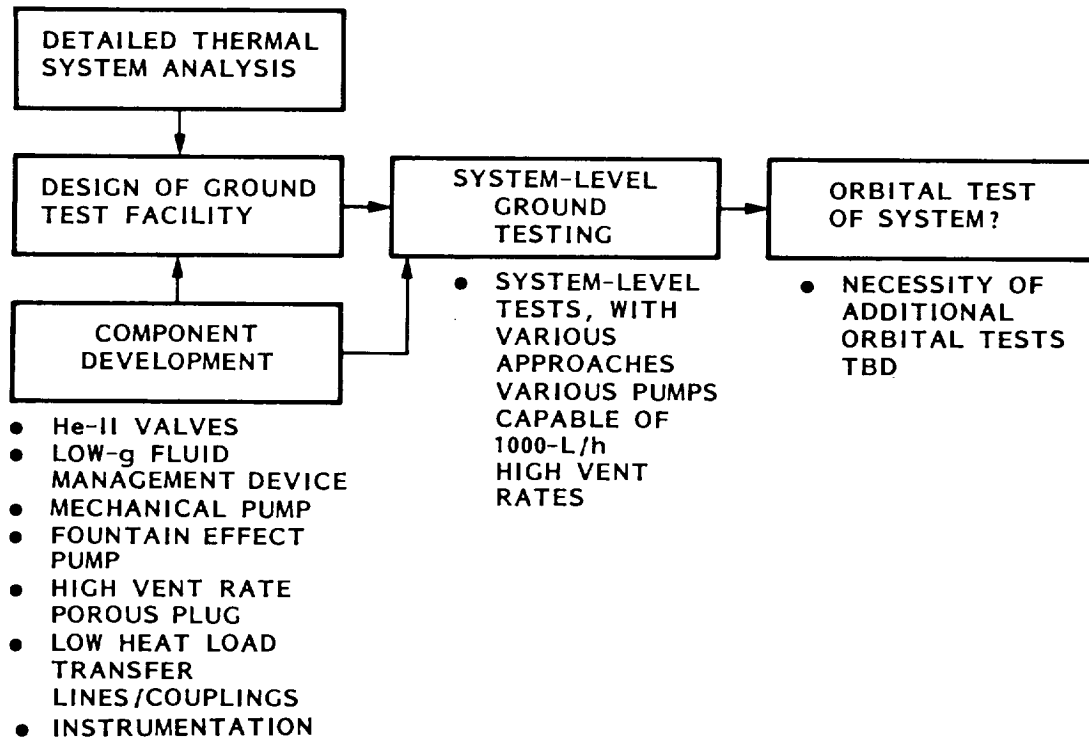


Fig. 7-1 Technology Development Flow

The second activity is design of a ground test facility for transferring He-II. This design naturally complements the detailed thermal system analysis, and would implement the components which were developed. These activities should probably be carried out together.

There are two basic approaches to design of the ground test facility. They are (1) design the facility from the start so that it can later be utilized in an orbital experiment, and (2) design it for ground test only. The second choice should substantially reduce cost and schedule and permit a greater variety of tests and options while answering most of the system questions. We recommend the second choice, a ground test facility.

The facility should have the following characteristics:

- (1) It should permit testing with different versions of the two candidate pumps - mechanical and fountain effect. This may require access to the interior of the tanks, or possibly the transfer section only.
- (2) It should be of sufficient size to permit testing for substantial time with flow rates up to ~ 1000 L/h. 250-L tanks would permit maximum flow rates for 15 min, which may be adequate. The facility cost is not highly dependent upon tank size.
- (3) The heat leak to all elements of the system should be minimized so that heater-applied power can be applied at the location and magnitude desired.

- (4) The system should be capable of venting rates which are compatible with orbital operation. The pumping system required for this may be a major system driver and needs further study.

The question of whether to require an orbital test is of major consequence, since the schedule is long and the costs high. Although the major questions associated with He-II transfer in space can be accomplished on the ground, additional study and test should be performed on components and systems before a final assessment can be made on this question. Table 7-1 summarizes the various costs and schedule requirements for the technology development.

Table 7-1 TECHNOLOGY PLAN COST/SCHEDULE SUMMARY

ITEM	DURATION	COST
Detailed Thermal Systems Analysis	6 months - 1 year	1 man-year
Mechanical Pump	Continue NBS tests; Implement into Ground Test Facility (GTF)	
Fountain Effect Pump (FEP)	2 years	5 man-years
High Flow Rate Phase Separator	2 years	5 man-years
Gallery Surface Tension Device	2 years	4 man-years
Low-g Performance of Metal Foam (LH ₂ system only)	1 year	1 man-year
Cold Shut-Off Valves	2 years	1/2M to 1M
Low Heat Leak Transfer Lines and Fittings	2 years	2 man-years
High Thermal Conductance Links	1 year	1 to 2 man-year
Instrumentation	2 years	1M to 5M
Ground Test Facility Design Fab. and Checkout Systems Test	6 months - 1 year 1 1/2 years 2 years	1 man-year 1.5 man-years 4 man-years

Prioritization

The following list presents the various technology items in descending order of priority. Some of these items are required regardless of the system selection, while others are dependent on the specific system selected, i.e., the mechanical pump or the FEP.

1. Gallery surface tension device
2. Mechanical Pump and FEP
3. Ground test facility for tank-to-tank transfer
4. High thermal conductance links
5. Instrumentation
 - (a) cold (1.8 K) pressure transducers
 - (b) LHe flowmeter
6. Low heat leak transfer lines and fittings
7. Cold shut-off valves
8. High flow rate phase separator (required for FEP systems only)
9. Low-g performance of Metal Foam (LH₂ system only)

Section 8

SUMMARY/CONCLUSIONS

The major conclusions of this study will be addressed in four areas:

1. Operations analysis
2. Orbital cryogen transfer
3. Space station impacts
4. Instrument changeout

8.1 OPERATIONS ANALYSIS

The findings of the operations analysis study are as follows:

- Attaining sun-synchronous operational SIRTf orbit is impractical with the single existing shuttle flight
 - Two flights would be required to deliver OMV and SIRTf separately
- 28.45-deg orbit at 600 to 700 km is readily achievable
 - Resupply of low-inclination SIRTf can be accomplished:
 - with the shuttle direct injection
 - with the OMV transported by the shuttle
 - with a space station based OMV
- The SIRTf cryogen resupply imposes no undue constraints on either the shuttle or the space station
 - Replenishment by STS requires dedicated application of this limited resource for up to 14 days per mission
 - Replenishment by space station based OMV implies high-reliability design needed for SIRTf because of limited accessibility
- Manned setup and termination of cryogen replenishment process is straightforward and preferred over application of conceptual robotic systems
- Impact of manned operations and use of the STS on the SIRTf mission are minimal
 - Man rating of SIRTf and resupply ASE adds weight and cost
 - Science return is greatly expanded
- Servicing a platform-mounted SIRTf using the OMV is severely time-limited unless it is sun-synchronous or co-orbiting (same altitude) with space station.

The benefits resulting from servicing SIRTf at low inclination and at sun-synchronism are presented in Tables 8-1 and 8-2.

8.2 ORBITAL CRYOGEN TRANSFER

Several techniques have been identified which will theoretically allow the efficient filling of SIRTf in orbit. Questions remain about optimization of the system with regard to fill efficiencies and operational simplicity. Two techniques involving pumps have been identified for further system analysis - the fountain effect pump and a mechanical pump. The transfer losses of the

Table 8-1 SERVICING ELEMENT BENEFITS FOR LOW-INCLINATION (28.45-deg)
SIRTF ORBITS

Servicing Elements	Advantages	Disadvantages
Shuttle	Excellent accessibility to any SIRTF for altitudes up to 600 + km	High cost; Limited servicing capability on orbiter
Shuttle and OMV	Excellent accessibility to any SIRTF for altitudes up to 700 + km	High cost; Time available to service platform based SIRTF is severely limited; Limited servicing capability on orbiter; Remote servicing at platform or free flyer using OMV is very limited unless very expensive robotic systems are developed
Space Station and OMV	Good servicing facilities - space, equipment, and personnel	Accessibility to non-co-orbital SIRTF is severely limited; Time available to service platform based SIRTF is severely limited; Remote servicing at platform using OMV is very limited unless very expensive robotic developments are completed

Table 8-2 SERVICING ELEMENT BENEFITS FOR SUN-SYNCHRONOUS SIRTF ORBITS

Servicing Elements	Advantages	Disadvantages
Shuttle	None	Shuttle performance is inadequate for replenishment missions above ~330 km
Shuttle and OMV	None	Single zero margin shuttle plus OMV can only reach ~500 km. Two dedicated shuttle scenarios, or shuttle rendezvousing with fully fueled OMV on orbit, is an expensive solution
(Polar) Space Station and OMV	This combination is the only set of servicing elements which can reach the desired 700-km SIRTF altitudes with baseline masses	The schedule uncertainty of a polar space station is a significant risk. Will the polar space station be deployed in the desired twilight sun-synchronous orbit

system appear to be relatively small, about 10 percent or less, for refilling a cold tank. For cool-down and top-off of a warm tank, the losses can be quite large, 50 percent or greater. No compelling arguments for elimination of the warm-tank refill capability have been presented. In addition to the possibility of an unexpected cryogen depletion, it may be desirable to warm up the system to change instruments. It appears that the required resupply tank capacity to refill a 4000-L SIRTf tank is about 10,000 L for a warm tank refill. The technology for orbital He-II refill is in the embryonic stage, and much work remains to be done.

A technology development plan was performed. The key elements of this plan are:

- Detailed systems analysis on the transfer thermodynamics, fluid flow, and pressure drop
- Development of key components such as the transfer pumps, zero-g liquid drain system (for He-II), venting system for H₂ (foam metal), special instrumentation and valves, and high vent rate porous plug
- Development of a ground test facility which includes a supply and receiver tank, transfer lines, necessary pumps, and provisions for venting at the necessary rates. This is considered to be one of the key technology items for the He-II transfer technology.

We do not think that orbital testing is required to establish the necessary confidence in orbital transfer capabilities. All of the required demonstrations, except the low-g liquid-He-II draining, can be demonstrated under 1-g conditions. We feel that adequate test and analysis of this system can be conducted without orbital tests. It is prudent to make a final decision on the necessity for orbital testing after component development and ground tests. The anticipated orbital tests of He-II transfer with a fountain effect pump in progress by NASA/GSFC should add confidence to the transfer capability. It may be expedient and cost effective to demonstrate and prove the orbital resupply capability on the actual supply tanker, since it is recoverable and could be further optimized or modified on the ground.

8.3 SPACE STATION IMPACTS

The hardware impacts on the space station are simply the accommodation of the cryogen replenishment system (CRS) and the SIRTf. The baseline concept calls for the replenishment ASE [without cryogen replenishment dewar (CRD)] to be carried to the station on a routine resupply and stored there for the duration of the SIRTf mission. The CRD would then be delivered shortly before the replenishment operation and subsequently returned to earth for storage, maintenance, and refill prior to the next service mission. Thus, the long-term physical impact on the space station is the occupation of space for the CRS.

Other effects appear to be as minimal as space utilization:

- The SIRTf and its ASE cannot contaminate the station or other users
- It has no impact on the station life
- The CRS will require periodic maintenance at the replenishment cycle

- The power and thermal loads are expected to be small compared to other space station users

More detailed considerations are:

- ASE stored on space station
 - Cryogen replenishment system
 - Instrumentation and control subsystem
 - Specialized EVA tools
- Likely effects on space station
 - Contamination - none
 - Potential contamination of SIRTf by effluent of life support system or propellant resupply system
 - Lifetime - none
 - Service and maintenance
 - Use of OMV will increase required service and maintenance of OMV
 - Permanent housing of instrumentation and control ASE would require maintenance and service at the replenishment period (1 to 2 years)
 - Thermal and power
 - Replenishment system expected to utilize minimal power at widely separated intervals 10 to 12 days on 1 to 2-year cycle
 - No specialized thermal loads or constraints are inherent in storage of the equipment or the He dewar. A bay to provide sunshade is desirable and may be required pending additional study.
 - Structures
 - SIRTf replenishment will use normal standard structures and mechanisms incorporated in the space station service bay. For example, berthing mechanisms similar to the MMS FSS will be required, and two mobile remote manipulators (MRM) will be required to handle SIRTf and OMV simultaneously.

8.4 INSTRUMENT CHANGEOUT

Four concepts were examined for changing out the scientific instruments. Two concepts require the entire SIRTf to be warmed up, while two concepts allow cold changeouts to be performed. One warm changeout concept (2) and one cold changeout concept (4) were recommended for further development. Table 8-3 compares concept 2 and concept 4.

Concept 2 weighs less, has a slightly longer lifetime, and the development cost is less. On the other hand, concept 4 is shorter in length and has lower STS launch costs. Concept 4 also includes concerns over cryocontamination, astronaut safety, and heat inputs during instrument changeout. Nevertheless, both concepts look technically feasible and should be investigated further. Concept 2 allows cryogen mechanisms such as valves and the beam splitter to either be serviced or changed out. Concept 4 allows changeout for all mechanisms except the cold valves. For either concept, changeout of the secondary mirror appears to present the most difficult problems.

Table 8-3 COMPARISON OF WARM (CONCEPT 2) VERSUS COLD (CONCEPT 4)
INSTRUMENT CHANGEOUT CONCEPTS

Delta Comparisons	Concept 2 (Warm)	Concept 4 (Cold)
Additional Weight	+8 percent	+206 kg (454 lb)
Additional Length		
Lifetime Difference		-0.5 percent
Development Cost		+11 percent
STS Costs	+7 percent	

Section 9
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16. Abstract The Space Infrared Telescope Facility (SIRTF) is a long-life cryogenically cooled space-based telescope for infrared astronomy from 2 micrometers to 700 micrometers ^{micrometers} . SIRTF is currently under study by NASA-ARC (Reference AP) and planned for launch in approximately the mid 1990s. SIRTF will operate as a multiuser facility, initially carrying three instruments at the focal plane. It will be cooled to below 2 K by superfluid liquid helium to achieve radiometric sensitivity limited only by the statistical fluctuations in the natural infrared background radiation over most of its spectral range. The lifetime of the mission will be limited by the lifetime of the liquid helium supply, and baseline is currently to be 2 years. This study investigated the telescope changes required to allow in-space replenishment of the 4,000-L superfluid helium tank. ^{was investigated} A preliminary design for the space services equipment was also developed. The impacts of basing the equipment and servicing on the space station were investigated. Space replenishment and changeout of instruments required changes to the telescope design. Preliminary concepts are presented.					
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